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PROCEEDINGS OF THE SECTIONS OF THE INSTITUTION*

INSTALLATIONS SECTION

18TH MEETING OF THE INSTALLATIONS SECTION, 14TH OCTOBER, 1943

Mr. R. Grierson, the retiring Chairman of the Section, took the chair at 5.30 p.m. for the first part of the proceedings.

The minutes of the meeting held on the 6th May, 1943, were taken as read and were confirmed.

Mr. Grierson announced the Council's award of premiums (see vol. 90, Part I, page 213), for papers read before the Section during the session 1942–43.

Mr. Grierson then vacated the chair, which was taken by the new Chairman, Mr. A. G. Ramsey, O.B.E., B.Sc.(Eng.).

A vote of thanks to Mr. Grierson for his services as Chairman during the 1942–43 session, proposed by Mr. H. T. Young and seconded by Mr. R. H. Rawll, was carried with acclamation.

Mr. Ramsey then delivered his Inaugural Address (see Part I, No. 37, Jan., 1944, page 21).

A vote of thanks to the Chairman for his Address, proposed by Mr. G. O. Watson and seconded by Mr. W. R. Watson, was carried with acclamation.

19TH MEETING OF THE INSTALLATIONS SECTION, 11TH NOVEMBER, 1943

Mr. A. G. Ramsey, O.B.E., B.Sc.(Eng.), Chairman of the Section, took the chair at 5.30 p.m.

The Minutes of the meeting held on the 14th October, 1943, were taken as read and were confirmed.

A paper by Mr. S. H. Chase, Associate Member, entitled "Emergency Lighting Systems and their Applications, with particular reference to Battery Equipments," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

MEASUREMENTS SECTION

108TH MEETING OF THE MEASUREMENTS SECTION, 22ND OCTOBER, 1943

Mr. E. H. Miller, the retiring Chairman of the Section, took the chair at 5.30 p.m. for the first part of the proceedings.

The minutes of the meeting held on the 21st May, 1943, were taken as read and were confirmed.

Mr. Miller then vacated the chair, which was taken by the new Chairman, Mr. E. W. Moss.

A vote of thanks to Mr. Miller for his services as Chairman during the 1942–43 session, proposed by Mr. G. F. Shotter and seconded by Mr. S. H. Richards, was carried with acclamation.

Mr. Moss then delivered his Inaugural Address (see Part I, No. 37, Jan., 1944, page 28).

A vote of thanks to the Chairman for his Address, proposed by Dr. W. G. Radley and seconded by Mr. L. J. Matthews, was carried with acclamation.

109TH MEETING OF THE MEASUREMENTS SECTION, 19TH NOVEMBER, 1943

Mr. E. W. Moss, Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 22nd October, 1943, were taken as read and were confirmed.

A paper by Mr. A. Hobson, B.Sc.Tech.(Hons.), Associate Member, entitled "Instrument Transformers," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

TRANSMISSION SECTION

54TH MEETING OF THE TRANSMISSION SECTION, 20TH OCTOBER, 1943

Mr. P. E. Rycroft, M.B.E., the retiring Chairman of the Section, took the chair at 5.30 p.m. for the first part of the proceedings.

The minutes of the meeting held on the 12th May, 1943, were taken as read and were confirmed.

Mr. Rycroft then vacated the chair, which was taken by the new Chairman, Mr. T. R. Scott, D.F.C., B.Sc.

A vote of thanks to Mr. Rycroft for his services as Chairman during the 1942–43 session, proposed by Mr. H. W. Grimmitt and seconded by Mr. F. de B. Hart, was carried with acclamation.

Mr. Scott then delivered his Inaugural Address (see Part I, No. 37, Jan., 1944, page 33).

A vote of thanks to the Chairman for his Address, proposed by Dr. T. E. Allibone and seconded by Mr. A. H. Roberts, was carried with acclamation.

55TH MEETING OF THE TRANSMISSION SECTION, 10TH NOVEMBER, 1943

Mr. T. R. Scott, B.Sc., Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 20th October, 1943, were taken as read and were confirmed.

A paper by Messrs. F. N. Beaumont, B.Sc.(Eng.), and F. A. Geary, Associate Members, entitled "Maintenance of Distribution Plant and Mains on A.C. Networks," was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

* Excluding the Wireless Section, the Proceedings of which will be found in Part I and also in Part III of the *Journal*.

PROTECTIVE SYSTEMS *

I. PROTECTIVE SYSTEMS FOR RURAL DISTRIBUTION UP TO 33 kV, by D. C. FIELD, B.A., Member.†

II. PROTECTIVE SYSTEMS FOR SUPPLY NETWORKS OPERATING AT VOLTAGES UP TO 11 kV, by OLIVER HOWARTH, Member.‡

III. PROTECTIVE SYSTEMS FOR RURAL DISTRIBUTION UP TO 33 kV, by R. W. STEEL§ and A. W. ALLWOOD, B.Sc.,|| Associated Members.

IV. AUTOMATIC SELECTIVE ISOLATION OF SUSTAINED EARTH FAULTS ON A NETWORK PROTECTED BY PETERSEN COILS, by K. I. BROWN, M.B.E., Associate Member.¶

(*Four papers read before the* TRANSMISSION SECTION *12th May*, 1943, *Mr. Brown's paper being read on his behalf by Mr. J. F. Shipley. Messrs. Steel and Allwood's paper was also read before the* WEST WALES SUB-CENTRE *11th December*, 1943).

I. PROTECTIVE SYSTEMS FOR RURAL DISTRIBUTION UP TO 33 kV

(*The paper was first received 11th November*, 1942, *and in revised form 22nd March*, 1943.)

SUMMARY

General principles regarding protection are discussed, emphasis being laid on the importance of considering the prevention of faults as part of the problem equally with their isolation. From an analysis of the causes of interruptions, which show that a large number are only transient, and from the special conditions pertaining to a rural system, it is concluded that it is preferable to restrict the number of points at which automatic protection is provided, in order to facilitate the rapid resumption of supply.

The methods of protection adopted in one large rural area are briefly described, together with a summary of the experience gained in operating several classes of equipment, including arc-suppression coils, automatic-reclosing switches and fuse gear.

(1) GENERAL

(1.1) Requirements of Rural Protection

Before discussing the question of the most suitable methods of protection for rural systems, it might be as well to be quite clear as to what is understood by the term "protection." It can be defined either as the means whereby damage to lines and equipment is kept to a minimum and by which the highest standard of continuity of supply to the consumer is maintained, or, alternatively, as the method adopted to limit the effects of breakdowns and to isolate a faulty section of the system as speedily as possible.

It is from the former and wider aspect that the author proposes to consider the subject and to review not only the usual or restrictive protection equipment, but also preventive measures by which interruptions can be avoided and damage to the system reduced. It is unfortunate that protection is often considered only in the narrower meaning so that a sense of proportion is lost and restrictive equipment comes to be looked upon as desirable in itself and not merely as an unavoidably necessary adjunct to the more directly useful part of the system. The result is that protective systems tend to grow alarmingly in cost and complexity, with the consequent need of increased skilled maintenance, and to be installed regardless of their true economic justification.

Whilst there may be every reason for using elaborate methods of protection on main transmission lines, cables and transformers carrying large and important blocks of load, they are quite out of place on rural systems where the economic factor has to be continually borne in mind if the services of electricity are to be brought within the reach of all.

The chief requirements of any system of protection on a rural network are that it should be simple and the apparatus used robust and reliable. Simplicity results in a saving in cost both initially and for maintenance, as special skill is not required to carry out such inspection, checking and testing as may be necessary. Robustness and reliability are also of importance in keeping down maintenance costs on a system which may cover a large area of country with control points often widely spaced and unavoidably in rather inaccessible positions.

(1.2) Interruptions

When deciding on methods to be adopted or type of equipment to be used, it is inevitable that a compromise be made between the greatest degree of effectiveness and the overall cost. In reaching such a decision full consideration should be given to the kind of interruptions likely to be experienced, and the following information obtained from the records of the Wessex Electricity Co. shows what the experience has been in one particular area.

The Company has an area of about 4 000 square miles which is largely rural in character and which has been highly developed; there are 1 800 miles of e.h.v. overhead lines, of which approximately 85 per cent are rural, the length of underground cable being a small fraction of this.

The figures in Table 1 cover the last four years, and in order to obtain more reliable data for future use all interruptions attributable directly to wartime hazards have been excluded. So far as possible only mains and substations which can be classed as rural have been taken into account, although it is not always easy to draw this distinction where mixed types of load are supplied.

It will be noticed that about two-thirds of the interruptions were transient; actually this does not give the full picture of the incidence of this class of fault as the total does not include those which were cleared by arc-suppression coils without interruption of supply and those where the circuit was immediately restored by automatic-reclosing switches.

* Transmission Section papers.
† Wessex Electricity Co.
‡ Lancashire Electric Power Co.
§ Cheltenham Corporation Electricity Dept.
|| Norwich Corporation Electricity Dept.
¶ Irrigation Branch, P.W.D. (Hydro-Electric), United Provinces Government, India.
Mr. Brown's paper is based on a thesis which was submitted in lieu of the Associate Membership Examination.

Table 1

NUMBER OF INTERRUPTIONS EXPRESSED AS PERCENTAGE OF ANNUAL TOTAL

Year	1939		1940		1941		1942	
Transient:—								
Lightning	8·8		12·5		15·8		13·8	
Birds	11·1		6·3		6·6		16·6	
Gale and snow	5·1		9·9		4·3		6·2	
Miscellaneous	4·9		2·3		1·7		1·9	
Unknown	35·3		32·4		41·7		33·7	
		65·2		63·4		70·1		72·2
Sustained:—								
Lightning	2·8		3·4		4·3		0·5	
Birds	5·7		2·1		2·9		4·5	
Gale and snow	3·9		6·3		3·2		1·9	
Mains and substation equipment	7·5		12·3		10·9		12·1	
Miscellaneous	14·9		12·5		8·6		8·8	
		34·8		36·6		29·9		27·8
		100·0		100·0		100·0		100·0

Not to be able to ascertain with certainty the cause of an interruption is always unsatisfactory for an operating engineer, but in many instances where proof cannot be obtained there is circumstantial evidence available to suggest a reason. Some of the unknown faults may be intermittent and due to incipient breakdown which later may lead to complete failure; others may be due to foreign matter blown into the lines or to lightning; whilst many are almost certainly caused by birds, which can be responsible for quite an appreciable percentage of the total faults.

(2) PREVENTIVE PROTECTION

(2.1) Design

Good design plays an important part in reducing the number of interruptions. Constant attention should be directed to improving both the design of individual components and their method of use, and every opportunity taken of profiting from experience. To do this it is essential for proper records to be kept of all faults, with as much evidence as possible of conditions obtaining at the time of the occurrence and of the cause of the failure; if these records are periodically summarized and analysed much useful information becomes available pointing to directions in which improvements in design may be effected.

Although somewhat outside the scope of this paper, mention may be made of two ways in which design can directly assist in improving continuity of supply. As has already been mentioned, birds can be responsible for a not inconsiderable proportion of interruptions, due mainly to flocks bridging across between conductors when in flight, or by causing them to clash when taking off simultaneously. This has been found to occur frequently in certain districts and at certain seasons of the year; clashing is also experienced due to accumulations of snow falling from conductors. Vertical disposition of conductors should therefore be avoided; if horizontal formation is adopted the risk of clashing is eliminated and the probability of trouble from flying birds should be greatly reduced.

The more widespread use of unearthed overhead lines should assist materially in reducing the number of transient earth faults of all kinds. It has already been found that interruptions have noticeably decreased on lines originally constructed as "earthed" but later operated "unearthed."

(2.2) Lightning Arresters

It is always a difficult matter to prove the effectiveness in practice of any form of surge protection; lightning is very fickle, varying in its incidence from year to year and place to place.

Three years ago, after several years of trial, lightning arresters of the Thyrite type were adopted as standard practice for new work at all larger outdoor substations and at the junctions of overhead lines and underground cables. In addition, certain existing lines have been similarly equipped and in many cases the number of failures due to lightning has appreciably declined.

(2.3) Arc-Suppression Coils

Because of their ability to clear transient faults harmlessly and to prevent sustained faults from causing any interruption of supply, arc-suppression coils have a special claim for attention on a rural system which, consisting as it does largely of overhead lines, is very liable to transients and has few closed rings to limit the effect of any interruption.

Edmundsons group of undertakings, of which the Wessex Company is one, first installed coils in 1934,* and the early experience proved so promising that the number has since been continuously added to. At the present time, in the East Anglian and Wessex areas alone there are 20 coils in circuit protecting 1 645 miles of mains; in no case is a switch provided for automatically short-circuiting the coil in the event of a sustained fault.

Although it is not possible to give statistics of the operation of all these coils, as recording instruments are not always fitted, the figures in Table 2 of the faults successfully dealt with by the coil at Melksham give an indication of the service such a device can render.

Table 2

MELKSHAM 11-kV ARC-SUPPRESSION COIL

Year	1939	1940	1941	1942
Number of transient faults suppressed	53	40	67	49
Number of sustained faults held	3	5	11	10

An objection sometimes made to arc-suppression coils is that in the case of fallen conductors they can introduce a risk of injurious shock to anyone coming in contact with the wires. Whilst it would be idle to deny that circumstances can be visualized in which such a condition might occur, no case of personal injury has been reported in the areas mentioned during the 8 years the

* *Journal I.E.E.*, 1938, 82, p. 187.

coils have been in use. On the contrary, in one instance at least it has been reported that unsuspecting people have handled the broken conductors with complete impunity and without experiencing any shock. On more than one occasion a 3-phase supply has been maintained with a broken conductor lying with the two ends on the ground.

There are many arguments for and against the practice of short-circuiting an arc-suppression coil after a predetermined period should a fault persist. The advantage of being able to continue supplies until a more suitable opportunity for shutting down has been proved many times. On one occasion it was possible to maintain supply to a consumer for several hours and so enable certain vital and urgent work to be completed.

The chief reason for adopting short-circuiting would seem to be to obviate the risk of a double earth fault; this in its turn depends upon the condition of the system protected. On a modern well-insulated system the occurrence of a double earth fault is comparatively rare, but on an old system with lower insulation values two or even more simultaneous faults are sometimes experienced. This is particularly the case for a short time after an arc-suppression coil is first connected, as the existing system may contain a number of incipient weaknesses which will probably result in a breakdown eventually; the introduction of the coil will expedite the elimination of these weak spots. This period can be shortened by intentionally applying artificial earths at times when least inconvenience would be caused to consumers and when arrangements have been made beforehand for speedy repairs.

The installation of arc-suppression coils and their use to the fullest advantage calls for good insulation and a high standard of maintenance, and this applies not only to the undertaker's system, but also to any consumer's equipment connected to it.

It is important that the residual current through the fault when the circuit is in tune should be kept to a minimum. This current is chiefly due to leakage on the system, which is another argument in favour of good insulation and maintenance. On one section of the system, where currents of 8–10 amp are common, there have been cases of arcs being maintained through punctured insulators and causing the conductor to be softened by heating and finally parting and dropping two spans. It has also been found that the initial current-rush on the occurrence of an earth fault is sometimes sufficient to blow the smaller sizes of fuses and, consequently, it is advisable to fit 15-amp fuses as a minimum.

At a few substations wattmetric relays have been installed in the feeders to indicate the direction in which the fault lies. At first considerable difficulty was experienced in obtaining correct indication, but as a result of many experiments several modifications were made and reasonably satisfactory service has been given. An important point is that suitable separate current transformers should be used having a small phase-angle error. More extensive use of indicating relays has not been made as the cost is hardly justified on small sections of a system.

(3) RESTRICTIVE PROTECTION

(3.1) Layout of System

In laying out and developing a rural system, the aim of reducing to a minimum without undue cost the consumer-hours lost should be kept in mind. In view of the high percentage of faults which are only of a transient nature it is more important that it should be possible to restore supply rapidly than that the area affected should be kept within small limits. To this end it is better, therefore, to have few easily accessible points at which automatic switches or fuses are installed than that they should be provided at all substations, transformer equipments and tee-off points in the hope that they will discriminate on a fault, which in actual practice they frequently fail to do.

To meet the case of the sustained fault, as well as for reasons, isolating switches should be provided at convenient points to enable the system to be sectionalized and the faulted with the least possible delay. It is important that isolators, as well as fuses, should be situated where they are readily accessible, since much time can be lost, especially in bad weather and at night, in getting to control points which have to be approached across country on foot. This point is one which is sometimes overlooked and where it is well worth taking a little trouble in selecting the most suitable position.

(3.2) System Protection

Turning to the question of the type of protection suitable for rural systems, it might be of interest to describe briefly the general methods adopted in the Wessex area.

The main backbone of the system consists of 33-kV lines radiating from the Grid supply points and interconnecting the various 33/11-kV substations where they are controlled by oil circuit-breakers which are also used for transformer protection. At the large substations the 33-kV lines, the transformers and the outgoing 11-kV feeders are all provided with overload and earth-leakage protection by means of definite-minimum inverse-time delay relays. At substations with transformers of 1 000 kVA capacity and less the 33-kV lines are normally controlled by isolators only, the transformers are protected by 33-kV fuses and the 11-kV feeders by oil switches with series overload and earth-leakage trip coils and time-lag fuses.

From these substations the principal 11-kV mains radiate with numerous interconnections. They are looped into substations either on oil-immersed isolators or, at certain points, on oil circuit-breakers with overload and earth-leakage protection.

In addition to the main substations there are a number of smaller intermediate stations, either on the main line or on branch lines, to serve local districts where transformation is from 11 kV either to 400 volts direct or to 11 kV, the transformers being protected by 33-kV fuses.

The light rural lines either start from these substations or are tapped off the main 11-kV lines. Where they leave 11-kV substations they are controlled by oil circuit-breakers with overload and earth-leakage protection and sometimes fitted with automatic-reclosing gear, and where they are tapped off overhead lines or are taken direct from small 33/11-kV substations either pole-mounted fuses or automatic-reclosing switches are installed.

All 11-kV pole-mounted transformers are connected to the line through isolating switches only. This practice may be criticized on the ground that, in many cases, transformers are protected by fuses or switches with settings considerably in excess of what would normally be provided for each individually, so that consequently, when breakdown occurs, they will suffer much greater damage before the circuit is interrupted.

This is possibly true, but the question is one of economics. A modern transformer is a particularly reliable piece of apparatus and the savings which may be effected on the few failures which do occur must be set against the large capital expenditure necessary for providing each with separate fuse protection. Further, when transformers are provided with individual protection it is common experience to find that, after the passage of a thunderstorm, many of the fuses have blown without permanent damage to the transformers, whereas with group protection this trouble is not so widespread, the number of fuses to be replaced considerably reduced and consequently the number of consumer-hours lost will be less. The precaution of fitting arcing horns to transformer bushings assists in preventing damage to the bushings themselves, and by arranging them with two gaps in series, one on either side of the bushing, the risk of bird trouble is eliminated.

(3.3) Automatic-Reclosing Switches

For use in the more inaccessible parts of the system and for controlling lines which have been found particularly susceptible to transient faults, automatic-reclosing circuit-breakers serve a most useful purpose. Although records are not complete for all the switches installed in the East Anglian and Wessex Areas, amounting to 67 at the present time, the summary given in Table 3 of those that are available shows how valuable these switches can be in dealing with transient faults; in addition they have operated many times on sustained faults.

Table 3

OPERATION OF AUTOMATIC-RECLOSING SWITCHES ON TRANSIENT FAULTS

Year	1939	1940	1941	1942
Number of switches ..	16	28	39	57
Number of successful reclosures	55	91	143	187
Average number of reclosures per switch ..	3·4	3·3	3·7	3·3
Maximum number of reclosures of any one switch	19	55	45	42

Standard indoor circuit-breakers can be fitted with a reclosing mechanism in which a spring, rewound either by hand or by motor drive, provides the operating force. For pole mounting, oil circuit-breakers are available which utilize a falling weight for reclosing. Both types usually incorporate, in addition to a time lag in tripping, a time delay for the reclosing operation and means for locking the switch out should the fault persist. This results in a somewhat complicated and delicately adjusted mechanism which is liable to get out of adjustment, particularly in the case of the spring-operated switches.

It is doubtful whether all these features are essential, and a more reliable equipment would result if some were eliminated. For reclosing after a transient fault no further delay than that required to operate the switch should be necessary and, if the fault persists, the switch might be allowed to run through all its available reclosures, particularly if a maximum of three only is provided and when the fault current is low, as is generally the case.

Two methods are used for obtaining time delay, the escapement and the oil-filled dashpot. The latter is not subject to mechanical defects, but it is naturally dependent on temperature, and in the case of switches installed out of doors the variations experienced can be considerable. When dashpots are used for delaying the tripping operation, difficulty is sometimes experienced in obtaining satisfactory discrimination under all conditions; so far this problem has not proved insuperable, but it is possible that it would be more pronounced with higher fault currents when grading with protection having an inverse-time characteristic.

A certain amount of trouble has been experienced due to rusting both in the mechanism and of the external chain, causing failure to operate. A greater use of rustless material would greatly reduce the chance of any part sticking.

(3.4) Switch-Fuses

For controlling short cable extensions and transformers oil-immersed switch-fuses installed both indoors and outdoors have proved very useful. These are circuit-breakers incorporating fuses which interrupt the faulty phase and then trip the switch on all three phases. Their cost is comparable with that of oil-immersed isolators which might be used in such a position, but in addition to a means of isolation they provide over-current protection.

The chief drawback of this type of switch is that it is necessary to lower the tank to replace a fuse before reclosing, an operation that takes time and introduces the risk of moisture getting in when performed out of doors in wet weather. For this reason it is less satisfactory for controlling overhead lines which are liable to more frequent interruptions.

(3.5) Fuse Gear

It is the characteristics of simplicity and economy that are the chief reasons for fuses being employed so extensively for the protection of rural lines. They require no special maintenance although, on the other hand, it is necessary to carry a large stock of spares dispersed throughout the area to be instantly available when required. It is of considerable assistance in keeping down the number of spares if the fuses are of the rewirable type which can be easily reconditioned by the operating staff without the necessity of returning them to the makers. Another very desirable feature is that fuses which have blown can be detected from the ground without the need for closer inspection or test.

Two types have been used on e.h.v. lines, namely the carbon-tetrachloride and the h.r.c. cartridge fuse. Both are capable of satisfactory service, but the former has a higher initial cost and generally requires reconditioning by the makers; it has, moreover, a very high speed of operation, introducing difficulties in grading.

The operation of a cartridge fuse, enclosed as it is in a ceramic tube, cannot be detected visually without some form of indicator. This can be provided and it is also possible to make this fuse suitable for rewiring by a man working to simple instructions. Some of the earlier 11-kV fuses used gave trouble due to moisture entering under the caps; this was cured by using cement more suited to outdoor service. The same effect has been experienced with 33-kV fuses, but although many improvements have been effected it cannot yet be said that the problem has been entirely solved and complete reliability achieved. Too frequently reports are received of shattered tubes or of fuses failing to clear but continuing to carry current and rendering the whole tube incandescent. It has been suggested that the latter phenomenon may, in the case of the higher-rated fuses embodying two elements in parallel, be caused by a surge dissipating the current-carrying element but not being of long enough duration to rupture the fusing element which is left carrying the normal load current. This theory is somewhat difficult to believe as one would expect the fusing element to rupture long before the tube reached white heat.

The indicating devices so far used have not proved entirely reliable, thereby defeating their object, and it is to be hoped that this defect will be overcome, as a dependable form of indication can be a great time-saver.

The mounting of fuses calls for ease of access and replacement. 33-kV fuses, which are used chiefly in substations, are most conveniently carried on fixed mounts and controlled by isolating switches. On 11-kV lines two methods have been used, the pull-down and the withdrawable. The former consists of a steel framework hinged to the pole with the fuses mounted at the top and contacts which engage with fixed contacts on the pole. For replacement the framework can be swung to a convenient height and the fuses easily changed from ground level. The most successful type has been one operated by a lever which has proved superior to earlier models using either a monkey winch or a pole. This gear has the merit of permitting quick changing of fuses under all conditions, but requires care in erection and maintenance to ensure correct alignment of the contacts and prevention of sticking of moving parts.

The withdrawal type consists either of a single porcelain insul-

lator mounted vertically with a contact at each end and into which the fuse is inserted or, alternatively, of two separate pin insulators carrying the contacts one above the other. In each case the fuse is inserted and withdrawn by means of a pole operated from the ground, and is retained in position by a bayonet fixing. This fuse gear is simple, robust, easily erected and should require no special maintenance, but it entails the use of a special rod which must either be carried about by the operator or provided at each control point. It will also be appreciated that it is not a simple matter to replace a fuse at the end of a 20-ft pole under adverse conditions, for instance on a dark night with a high wind blowing, and it is impossible to provide any indication of a fuse having operated.

On 400-volt overhead lines the "Clevis" carrier, with cartridge fuse, fixed about 10 ft from the ground, provides a convenient and economical method of protection and has pr for currents up to 100 amp. For heavier load to use service-type cut-outs housed in a weathe single-insulator withdrawable type, already desc service, has been tried for duty up to 200 amp, b heating and burning of contact surfaces occurre currents and it would seem that this design is o lower ratings.

(4) ACKNOWLEDGMENTS

The author's thanks are due to the East Anglian Co., Ltd., and the Wessex Electricity Co. for per lish information contained in the paper, and members of the staffs of these Companies for thei many helpful suggestions.

II. PROTECTVE SYSTEMS FOR SUPPLY NETWORK OPERATING AT VOLTAGES UP TO

(*The paper was first received 12th September, and in revised form 9th December,* 1942.)

SUMMARY

The paper consists of a description of the area supplied by the Lancashire Electric Power Co., and of the nature of supplies afforded in that area. The 11-kV distribution system and the protective arrangements employed thereon are described, and figures showing availability of supply to consumers during a period of 1 year are given. The testing necessary to ensure satisfactory functioning of the protective gear is also described.

(1) DESCRIPTION OF AREA

The area covered by the Lancashire Electric Power Co. comprises approximately 1 200 square miles in that part of Lancashire which is situated south of the Ribble. It excludes all the cities and most of the towns within that area. The undertaking is the authorized distributor over the rural part of the area and in a number of the smaller townships. The largest town in which the undertaking has powers to distribute has approximately 31 000 inhabitants. Bulk supplies are afforded to 13 boroughs and townships with populations varying from about 3 000 to 90 000. The total population of the areas in which the undertaking distributes l.v. supplies is 300 000, and supplies are afforded to 60 000 domestic consumers.

The maximum demand on the undertaking for the 12 months ending March, 1940, was 164 000 kW, and the units sold amounted to 585 000 000, of which 240 000 000 went to bulk supplies, 43 000 000 were sold direct to domestic, shop and small power users, and 283 000 000 were supplied to industrial users.

(2) SYSTEM OF DISTRIBUTION

The undertaking has three generating stations, one which generates at 33 kV and from which no 11 kV feeders radiate, and two generating at 11 kV. All three are selected stations. There is a 33-kV main transmission system which feeds eight 33/11-kV step-down control stations.

High-voltage distribution is at 11 kV, with a certain amount of subsidiary 2-kV and 3-kV distribution. Of the total length approximately 50% is underground and 50% overhead. The 11-kV system is divided into twelve 11-kV networks, which can be interconnected but are normally run as separate networks. Two networks are fed from generating stations, eight from 33/11-kV step-down substations and two from points where bulk supplies are purchased. These substations and bulk-supply points are attended. The 2-kV and 3-kV lines are supplied from 11/2-kV or 11/3-kV step-down substations, which are unattended.

The great majority of the 11-kV feeders are in duplicate, and consumers' substations and also substations su works are supplied by means of a tee-off fro Change-over arrangements under the consumers' vided in each substation, enabling him to chang feeder to the other should his supply fail. The c feeders is such that one feeder will carry all the loa

The final l.v. distribution system is 3-phase volts. Many of the l.v. networks are fed from or adjacent to, industrial consumers' premises.

(3) EARTHING

The 11-kV networks are earthed by means of li which limit the current to 300 or 450 amp. 3-kV systems and the l.v. systems are solidly eart

(4) PROTECTIVE SYSTEMS ON FEE

No pilot protection is provided on any of the voltage lines. The normal protection consists c earth-leakage protective gear.

At the generating stations and other centres there are two overload plunger-type relays with ti two inverse time-lag induction relays with final and one earth-leakage relay with provision for fi fuse to afford a slight time-delay if desired. All electrically operated, and the relays are provide contacts to open the switches.

In the substations where the supply is stepp 11 kV and from 2 or 3 kV similar protection is switches are manually operated and the means of sists of a coil and plunger, the latter tripping the s ally. Time-delay is only provided in special case delay is provided time-lag fuses are used.

In the past it has been found that the protect some of the earth-leakage protective gear has owing to the unsatisfactory nature of the curre It has not always been appreciated by the supplie gear that an earth-leakage relay or coil and plu considerable burden on a current transformer, an earth-fault current energizes one current transfo dary of that transformer must not only provide s and current to operate the earth-leakage trip but n the current to magnetize the current transforme two phases, the secondaries of which are in para which provide an alternative path to the earth-l for the secondary current.

Cases have come to light where the earth-leak

not operate under any circumstances because the current transformers saturated before sufficient voltage was available to pass tripping current through the earth-leakage trip coil. There have been other cases where more current was required to operate the earth-leakage trip than the overload trips. More attention is being paid to the proper matching of the various items nowadays, and this trouble is rarely met with in newly supplied gear. It has, however, compelled the undertaking to test every switch and the protective gear associated with it before putting it into service.

Where feeders are in parallel from one set of busbars to another, parallel-feeder protection is employed. Much of this parallel-feeder protection is of the type employing biasing transformers. There are six sets covering two feeders, three sets covering three feeders, and one set covering four feeders. In each case the gear operates on the balanced-current principle at the point where the system is earthed, and on the balanced-power system at the point remote from that. Some of the two-feeder installations may be fed from either end, and in these cases provision is made—by means of a change-over switch at each end of the feeders—to change the gear over from balanced power to balanced current, or vice versa, in order to accommodate the different operating conditions. In this type of equipment no wattmeter movement is employed with the balanced-power gear. The directional effect is obtained by adding a voltage from the voltage supply to a voltage provided by the current, by means of the biasing transformers, these being arranged to orient the voltages so that the maximum sensitivity of the gear occurs at a power factor of about 0·7. The disadvantage of this type of gear is that the fault current required to trip it is a variable quantity depending upon the phase of the current. So far no trouble has arisen on this account, as satisfactory operation can be obtained with a wide range of operating currents. If the fault current on one phase is related to the voltage of the same phase there will probably be only a small voltage available to operate the gear, as the inevitable result of a fault is a reduction of voltage. The operating voltage is obtained from a transformer which is supplied from the other two phases and is designed to deliver a voltage different in phase from the primary and such that the relay is most sensitive to fault currents lagging by about 45°. A similar arrangement is provided for each of the three phases. Fig. 1 is a line diagram illustrating the principle of the balanced-power gear.

The advantage of this type of gear, employing biasing transformers, is that the relays are of the simplest possible pattern. They are of the attracted-armature type and merely have to be set to operate when the current exceeds a certain value. There is a reasonable amount of power available for operating them and, being of a simple pattern, they give little or no trouble provided they are well designed and constructed. The principal trouble with gear of this type has occurred in connection with the alignment of auxiliary switches on the main breakers and with the contacts of these switches. Whilst the troubles experienced have been few, it is a tedious job to trace such a fault to its source, as fairly complex arrangements have to be made in order to carry out a rigorous test on this type of gear.

The latest parallel-feeder protection installed on the 11-kV system is of the Translay type, and is installed on four feeders which operate in parallel between one of the generating stations and a bulk-supply user. Translay balanced-power relays consist of a double relay movement. The upper element has the secondary winding on it and is the one whose contacts trip the switch. The lower element is the wattmeter element, and if power flows out from the busbars the contacts will close and short-circuit a portion of the winding of the upper relay, thus enabling the upper relay to operate if the current is (*a*) flowing out from the bars, and is (*b*) in excess of the current flowing out from the bars in the other feeders. The wattmeter element is sensitive, and in consequence the value of fault current required to trip the switch is independent of the phase of the fault current. A relay is provided for each phase and one for earth faults, the current in the earth-fault relay being related to a "residual" voltage. Whilst the relays are numerous, they are of the induction type and are robust. Electrically operated auxiliary switches have been used on this equipment and have proved very satisfactory in service.

One advantage of this type of protection is that the switches are mounted on the relay panels, are under observation and are not disturbed by overhauls of the oil switches, as sometimes happens with auxiliary switches mounted on the main oil switches. Fig. 2 is a line diagram illustrating the arrangement of the balanced-power gear.

(5) TRANSFORMER PROTECTION

Transformers which step down from 11 kV to 2 or 3 kV or to 400/230 volts, and transformers which step down from 2 or 3 kV to 400/230 volts, are protected by means of overload and earth-leakage protection. 33/11-kV step-down transformers have restricted earth-fault protection on both sides in addition to standby

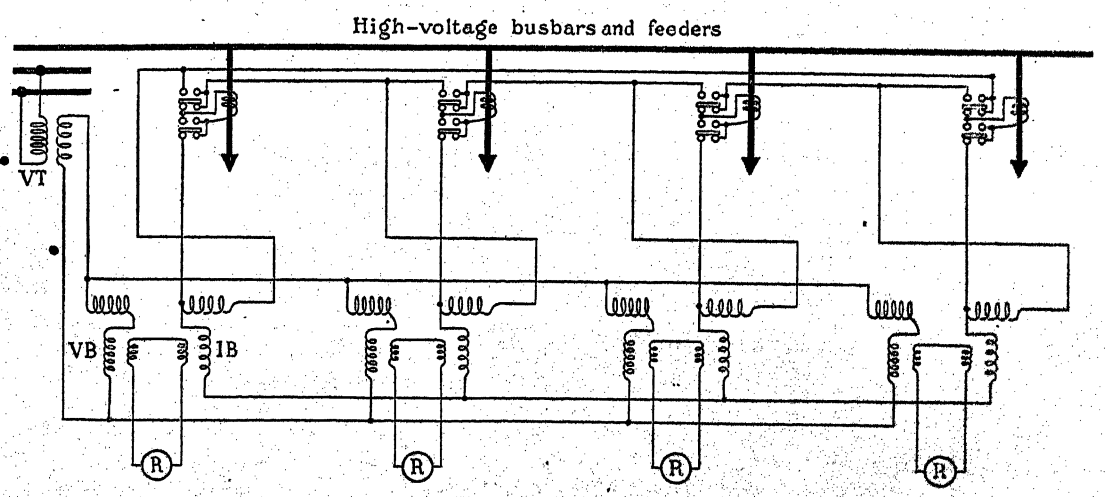


Fig. 1.—Parallel-feeder balanced-power biasing-transformer protection.

VB = voltage-circuit biasing transformers. IB = current-circuit biasing transformers. R = relays. VT = voltage transformer. Auxiliary switches shown in the "circuit-breaker closed" position. Tripping contacts and circuits are omitted.

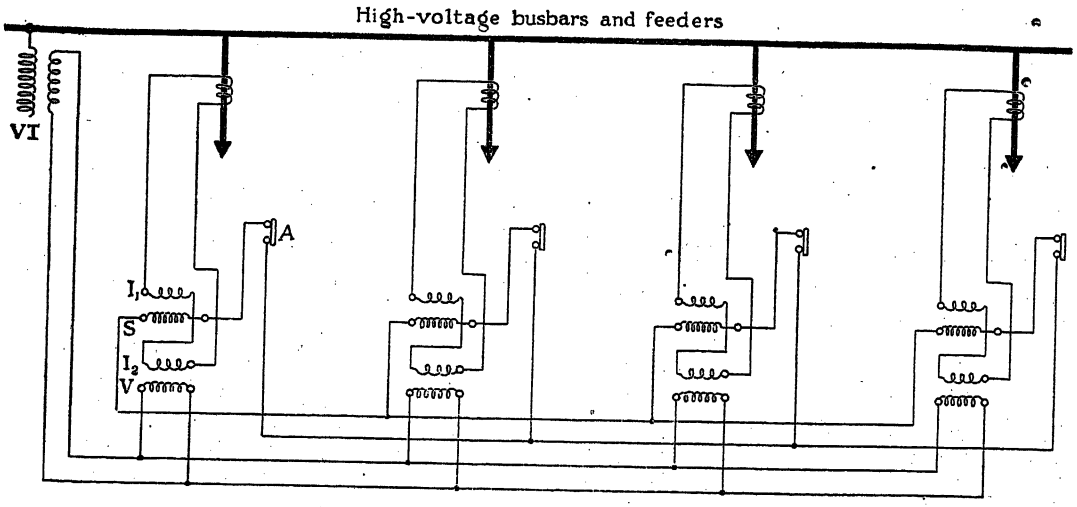


Fig. 2.—Line diagram of Translay balanced-power protection for parallel feeders.
I_1, I_2 = Relay current windings. S = Relay secondary windings. V = Relay voltage windings. A = Auxiliary switch contacts. VT = Voltage transformer. Tripping contacts and circuits are omitted.

overload protection on the secondary side. The restricted earth-fault protection on the 11-kV side is operated from four current transformers, one in each phase and one in the neutral earthing connection. On the 33-kV side there are only three current transformers, one in each of the three phases, as the star point of the 33-kV winding of these transformers is not used for earthing the 33-kV system. The protection on the 33-kV side is thus exactly similar to the ordinary earth-fault protection which is

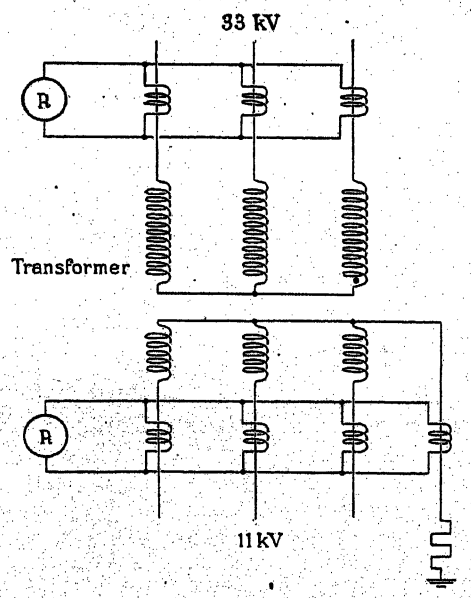


Fig. 3
R = Induction-type relays.

used on the feeders and on the transformers stepping down from 11 kV and from lower voltages. Fig. 3 illustrates the arrangement.

(6) FAULT-LOCATION INDICATORS

In order to enable faults on 11-kV feeders to be quickly located, and the sound portions put back into service, a simple type of current transformer was developed which could be mounted round the cable just below the dividing box. This has butt joints on the iron circuit and can be put round the cable and then bolted together. Connected to the secondary of this transformer is a fairly sensitive relay, which merely indicates whether the sum of the three currents in the cores of the cable is more than a fairly low predetermined value, i.e. whether there is an earth-fault current flowing. The earthing connection of the dividing box must also come back through the current transformer, so as to avoid any return current passing along the armouring from neutralizing the effect of the out-of-balance in the cores of the cable.

These relays are placed in control stations and substations where the feeders come in and go out again. When a feeder trips on account of an earth fault, the section on which the earth occurred can be found by inspecting these relays. The earth is on the section between the last relay which is indicating and the first relay which is not indicating. The feeder up to that point can then be made alive immediately, whilst the exact location of the fault is ascertained and the necessary repairs executed. These indicating relays have proved very reliable and satisfactory in service.

(7) RECORD OF INTERRUPTIONS

It should be borne in mind that the duplicate feeder system enables a consumer to change over from the faulty to the sound feeder should his supply fail. This results in a resumption of supply to consumers in a few minutes after a feeder has tripped.

The criterion by which a system of protection is judged is whether it keeps the interruption time to consumers down to the minimum. The statistics of the interruptions have been extracted on a basis of mile-hours of line. The mile-hours of interruption, expressed as a percentage of the total mile-hours of line, gives the percentage loss of supply which, when deducted from 100, will give the figure of merit of availability of the supply. The figures for the undertaking for the year ending the 31st March, 1940, show the total mile-hours of line interruption to be 0·09%. When a deduction is made from the loss due to the availability of supply on the sound line this percentage loss is reduced to 0·001%, i.e. an average of approximately 6 minutes per annum. The figure of merit is 99·999%.

(8) PROTECTIVE-GEAR TESTING

The need to test protective gear to ensure correct and reliable operation has been mentioned in earlier sections of this paper. It is sufficient to add that in order that the test may be as complete as possible it should consist of a rigorous test on each item with a final test on the equipment after installation by the method

of primary injection. In the case of manually operated gear of the coil-and-plunger type which trips the switch mechanically, primary injection tests on site are generally sufficient. Contact-making relays should be separately tested for accuracy and effective performance, preferably in the testing laboratory. Whilst this procedure may appear cumbersome and expensive to those who are unfamiliar with it, in actual practice it works quite smoothly. The cost and inconvenience of passing relays, current transformers, and, where necessary, voltage transformers, through the testing laboratory is more than justified by the reduction in the amount of work to be carried out on site.

There is rarely any difficulty in making primary injection tests on open-type gear or sheet-steel cubicle gear, but the same cannot be said of oil-filled and compound-filled ironclad gear. Primary injection tests are the more necessary on this type of gear owing to the impossibility of making a visual check of the connections. Where current transformers are mounted in the fixed portion of ironclad gear, between the spouts and the dividing box, some arrangement should be provided for passing full primary current through the current transformers after the dividing box has been made off. This can be done by means of heavy connections to the voltage-transformer spouts where these exist.

The author's experience indicates that certain tests common to all types of protection are worth making, as they reveal defects and errors which may exist in individual items of apparatus. Particulars of these tests are given below.

(8.1) Relays

Accuracy of current settings.

Accuracy of time scale.

If the VA burden of the type of relay and the speed of operation of the type of instantaneous relay is not known, tests should be made to ascertain these, but it is unnecessary to test each individual relay.

(8.2) Current Transformers

Current ratio.

Open-circuit secondary voltage with twice rated primary current.

Direction.

(8.3) Voltage Transformers

Voltage ratio.

Direction. (Where secondary windings are provided on a 5-limb 3-phase voltage transformer or on three single-phase voltage transformers to give a "residual" voltage, these should be checked for direction when one phase is short-circuited.)

The above tests can generally be carried out most economically in the testing laboratory, although there are cases where it is more convenient to make them on site. The advantage of testing in the laboratory is that if any doubtful result is obtained the resources of the laboratory are to hand for investigation.

In addition to the tests described above, the following tests have been found desirable on the types of protective gear under consideration.

(8.4) Overload and Earth-Leakage Protection

Current is passed through each pair of phases in opposite directions and the earth-leakage relay examined to see that there is no tendency to trip; or, if necessary, a milliammeter of low impedance is connected in series with the earth-leakage relay and the reading noted.

The currents required to trip the switch with the overload relays or plungers at various settings are noted.

The currents required to trip the switch with the earth-leakage relay or plunger at various settings, with the current passed through each phase in turn, are noted.

Satisfactory tripping of mechanically operated switches and satisfactory operation of relays, including any intermediate relays, is noted during the above test.

(8.5) Restricted Earth-Fault Protection

Stability and tripping current are tested just as the earth relay of overload and earth-leakage protection is tested, except that there are four current transformers involved, one being in the neutral earthing connection.

Where heavy short-circuit currents are possible and the earth-fault current is limited by a resistor, it is advisable to pass the maximum short-circuit current (which is determined mainly by the transformer reactance) through two of the phase current transformers in opposite directions, and at the same time to pass the maximum earth-fault current through the neutral current transformer and each of the phase current transformers in turn again in opposite directions. The current in the relay is measured both with and without the equivalent of the earth-fault current passing. The test is repeated with the remaining phase current transformer substituted for one which has been tested. It is usually necessary to make this test in the laboratory, owing to the heavy currents involved.

(8.6) Parallel-Feeder Balanced-Current Protection

Stability of the phase-fault protection is tested by passing current in one direction through all the red-phase current transformers in series and in the reverse direction through all the yellow-phase current transformers in series. Currents in phase and earth-fault relays are measured. The tests are repeated using blue and yellow or red phases. Fault settings are tested by passing current in opposite directions through each pair of phase current transformers of each feeder in turn.

Stability of the earth-fault protection is tested by passing current in the same direction through each red-phase current transformer and measuring the currents in the phase and earth-fault relays. The tests are repeated on the yellow phases and again on the blue phases. Fault settings are tested by passing current through each phase of each feeder in turn.

(8.7) Parallel-Feeder Balanced-Power Protection

The tests are similar to those carried out on the balanced-current protection, with the addition that the currents must be related to the voltages supplied to the voltage transformers. Tripping currents are tested on each feeder with the current in a direction equivalent to power flowing away from the busbars. An additional test must be made on each feeder to prove that it will not trip when power is flowing to the busbars. It is desirable, where practicable, to energize the voltage transformers from the h.v. system; this can usually be done by making the feeders alive. The current transformers must be isolated, of course, to enable the testing currents to be passed through their primaries. If it is not practicable to energize the voltage transformers from the h.v. system, the secondary leads can be taken off the secondary terminals and a suitable 3-phase voltage in the correct phase-sequence supplied from an alternative source.

Experience has shown that with fairly complex protection, such as balanced-power parallel-feeder systems and some types of balanced-current systems, it is very desirable to have the whole of the gear in the laboratory and to make very comprehensive tests to determine the characteristics and limitations of the gear. This applies particularly to new designs and to designs which have different sensitivities on different phases owing to unsymmetrical arrangements. Defects and errors which would have required days to trace on site can be traced in a few hours in the laboratory. Again, the information obtained in the laboratory enables the site tests to be reduced to the barest minimum. Site testing

is far more expensive than laboratory testing, and laboratory testing to reduce the amount of site testing necessary is commercially sound.

(8.8) Switch Speeds

The speed of operation of non-manually operated switches is tested as a matter of routine. The speed of opening and the time taken to close and open are tested. This is necessary in order to detect any sluggish switch which, if put into service, might allow faults to remain on the system long enough to cause operation of back-up protection, resulting in unnecessary interruptions of supply.

(9) CONCLUSION

The experience of the Lancashire Electric Power Co. indicates that with a duplicate tail-end feeder system simple overload and earth-leakage protection will ensure the minimum of interruption of consumers' supplies provided adequate tests are made to prove the reliability of the gear. Where two or more feeders operate in parallel between sending and receiving stations, and provided that the load tapped off along the route does not exceed about 50% of the normal load of the feeder, very satisfactory discrimination can be obtained with parallel-feeder protective systems.

(10) ACKNOWLEDGMENT

The author wishes to express his thanks to Mr. C. D. Taite, Managing Director of the Lancashire Electric Power Co., for permission to publish data concerning the undertaking, and for the facilities afforded during the preparation of the paper.

III. PROTECTIVE SYSTEMS FOR RURAL DISTRIBUTION UP TO 33 kV

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SUMMARY

The importance of installing suitable and efficient protective apparatus on rural networks, at all stages of their development is emphasized.

A typical protective scheme for an 11-kV and 33-kV rural distribution system which has been put into operation in a particular area of supply is described, and the reasons leading to its adoption are given.

The practical difficulties met with in securing efficient operation and of carrying out proper maintenance are discussed. Some statistical records of fault interruptions are presented. These indicate the number and type of faults causing total or partial failures of supply and show the conditions under which the protective gear is called upon to function.

The nature of the faults which occur on rural networks is analysed and a suggested standard form of keeping fault statistics is put forward for general adoption by undertakings distributing in rural areas.

(1) INTRODUCTION

In urban areas, the occurrence of faults on distribution systems inevitably results in the disconnection of relatively large numbers of consumers, even though the interruption is confined to a single distributor in a residential area. The multiplicity of interests thus affected initiates numerous courses of action on the part of individuals wanting their supply restored as soon as possible. The consequence is that many telephone calls are received or personal visits are made to the supply undertaking's offices, for immediate action to be taken to restore supply.

The number of such calls for action has generally been taken as representing the degree of importance of the occurrence, and, as a result, interruption of supply in urban areas has been considered of greater consequence than interruptions in rural areas.

Although much larger sections of the network may be affected by an interruption of supply in a rural area, due to the sparseness of population in the area, its technical features, and fewer telephones being available, there is considerably less clamour for restoration of supply.

On some occasions the supply undertaking may only become aware of an interruption of supply to a village or a section of a village, on the receipt of a postcard asking "when the supply which has been off since yesterday will be restored." This type of reaction to interruptions has not tended to create the impression that the continuity of rural supplies is an important matter, and such reaction is, no doubt, largely the result of relatively frequent faults which the consumers have come to regard as inevitable.

This attitude of mind, born of the pioneer period in rural electrification, has been undergoing rapid change in recent years. The rural consumers are beginning to expect and demand more reliable service, and the importance of rural loads is beginning to rank equally with that of urban loads.

The type of load connected in rural areas is no longer purely agricultural lighting, heating and cooking, but includes electric clocks, wireless sets, incubators, pumping and industrial loads. The interruption of supply to any of these is important to the consumer, and requires urgent action to be taken to restore supply.

These types of load require that much greater attention than was formerly considered necessary should be paid to means of protecting the distribution system against interruptions due to faults, and the selection, installation and maintenance of protective apparatus is an important factor in reducing to a minimum the number of consumers affected by an interruption. The extent to which protection can be carried depends on the amount of money which can be spent on it, and thus must, for the time being at least, be determined by local economic conditions.

(2) FUNCTION AND PLANNING OF A PROTECTIVE SYSTEM

A protective scheme for a rural e.h.v. network must cover all the high-voltage lines and apparatus connected to the system, including the main feeders or transformer bank, the main transmission lines, the ring mains or distributors, the spur lines and the high-voltage windings of transformers and all the switchgear.

The function of the protective gear is to disconnect or render harmless any fault which develops at any part of the system, with a minimum interruption of supply to consumers and with a minimum of damage to apparatus. To achieve this in a large rural area, with an interconnected network, is not as simple as would at first appear, and in every case the particular design of the network must be taken into consideration in determining the arrangement and type of protective gear.

When an area is being developed a general idea should be formed of the load to be expected, and the network so designed that when development has reached an advanced stage the sections which were constructed in the early stages fit into their proper places in the complete scheme. It should not be very difficult to anticipate, with a reasonable degree of accuracy, how the load is likely to build up under normal circumstances during the next decade or two, and to prepare a general scheme to cater for the expected output. The making of such a survey and the preparation of a scheme to deal with its requirements should make possible the selection of protective apparatus which will serve the needs of the network without undue modification or replacement, not only in the early stages but also when the loads have grown to many times the value reached in the first few years of operation. Such considerations may fully justify the installa-

tion of protective gear which, at first sight, seems unduly elaborate and complicated, but which fits well into the scheme as it takes on a more definite shape. In this way, adequate protection can be given to a network at each phase of its development without the drastic alterations occasioned when extensions are made piecemeal without reference to a comprehensive basic plan.

(3) TYPICAL PROTECTIVE SCHEME

(3.1) Description of Network

The protective scheme to be described and discussed in this paper has been applied to a network which covers an area of approximately 700 square miles. Development of the rural area began in 1926 by extension of the 6·6-kV feeders from the central urban area, but owing to the distance involved it was decided that the e.h.v. distribution should be at 11 kV. The rate of development of the rural area is indicated in Tables 1 and 2.

The load on the system has shown a steady increase, and the figures of maximum demand, units sold and annual revenue (Table 2) show the extent of the risk for which the cost of protection may be considered as a premium.

At the stage reached at present, the network comprises a main 11-kV ring which runs approximately parallel to the boundary of the area of supply. Radial feeders from a selected station feed into the ring at a number of points. Two of these radial feeders operate at 11 kV and are supplied through a bank of 6·6/11-kV step-up transformers consisting of two 2 000-kVA units, grouped together for switching purposes, and one 5 000-kVA unit. The remaining two radial feeders are 33-kV feeders, each fed by a 6·6/33-kV 7 500-kVA transformer, being connected to the 11-kV system by a corresponding 33/11-kV transformer at the remote end.

From the main 11-kV ring, spur lines and secondary rings feed the various distribution substations.

The general arrangement of the network is shown in Fig. 1.

Table 1

Year ending 31st March	Length of 6·6-kV		Length of 11-kV		Length of 33-kV	
	O.H. line	Cable	O.H. line	Cable	O.H. line	Cable
	miles	miles	miles	miles	miles	miles
1930	3·0	4·4	80·2	38·4	—	—
1935	5·2	7·6	345·2	81·3	—	—
1940	9·2	8·7	400·5	135·6	23·9	7·5

Table 2

Year ending 31st March	Maximum demand	No. of sub-stations	kVA of distribution trans-formers	Units sold	Annual revenue
	kW				£
1930	400	22	1 320	1 200 000	12 500
1935	2 797	277	11 200	7 053 000	59 300
1940	5 740	596	23 345	14 574 000	115 500

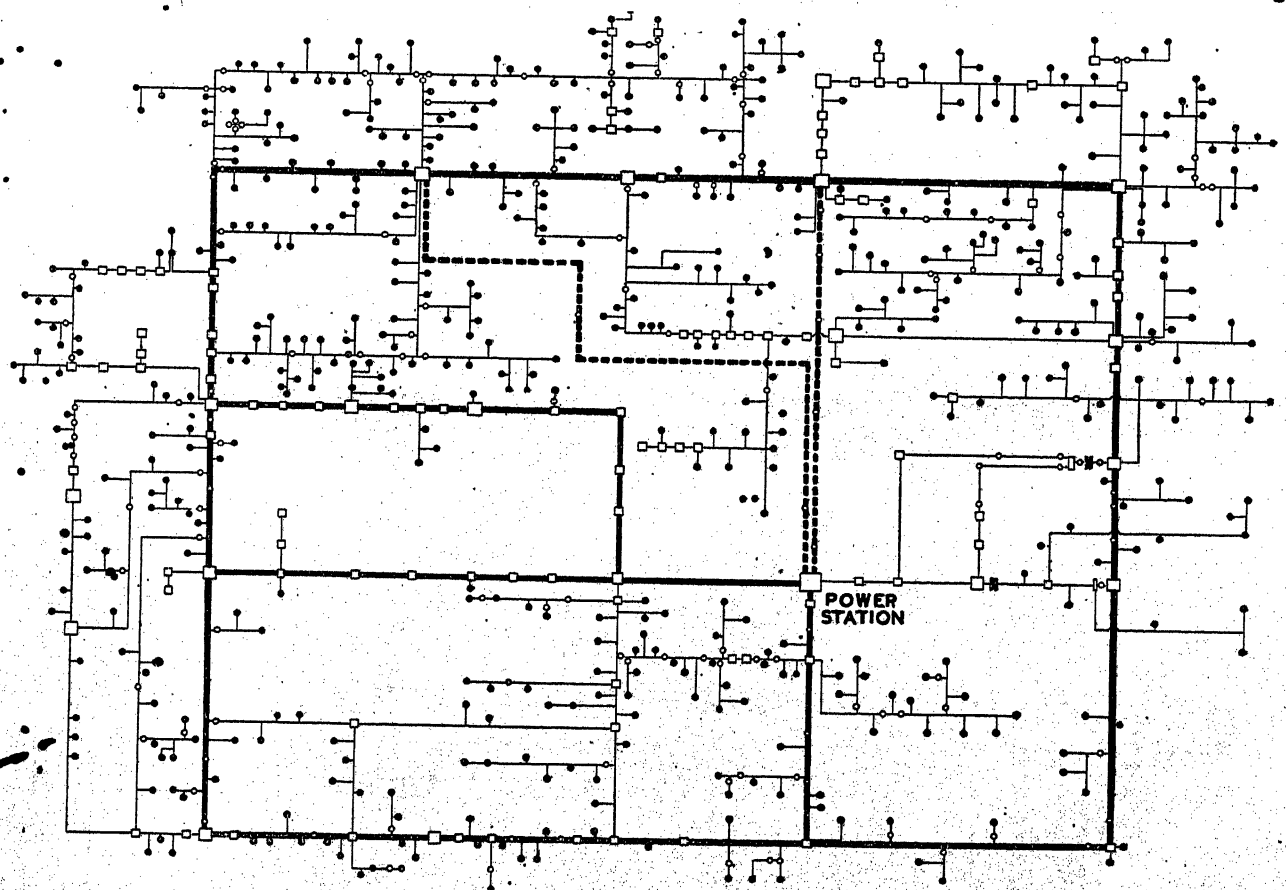


Fig. 1.—County e.h.v. network.

Main substations.
Kiosks and ring-main breakers.
Outdoor and pole-type substations.
Section switches.
33-kV feeders.
Main 11-kV lines.
Subsidiary e.h.v. lines.

(3.2) Considerations leading to the Choice of Protective Apparatus

The protection originally provided on the system consisted of over-current induction-type inverse and definite-minimum time-lag relays on the main transformers and 11-kV feeders and overload a.c. trip coils with time-lag fuses on the distributors. As was only to be expected, when a heavy fault occurred near the remote end of the network all the time-limit fuses blew together, allowing their associated switches to trip. This occasioned many delays in locating all the switches which had automatically operated, and in restoring supplies to the consumers on the healthy sections.

The problem then arose of applying a system of protection to the existing network and of selecting one which would form part of the scheme with a minimum of alteration. The network was growing at an ever-increasing rate and it was necessary that the scheme adopted should be sufficiently flexible to be adapted to the rapidly changing layout of the system. Better facilities for telephone communication between main substations was highly desirable, as existing facilities over the 24-hour period were not at all satisfactory. It was also essential, in view of the increasing short-circuit kVA available, to keep the operating time of the automatic switches to a minimum, so that the destructive effects of fault current would be minimized.

Among the limiting features was the fact that the main sections of the e.h.v. distributors to which the protection was to be applied were tapped at many places, and also the fact that the length of the sections was not sufficient to enable a time/distance system to be used with success. There were no pilot wires available for use with discriminating protective systems, and the cost of erecting separate pilot wires where the e.h.v. distributors consisted of underground cables and of modifying existing overhead lines to carry pilot wires was prohibitive.

The scheme which was finally adopted for discriminating protection on the main distributors was the "Interlock" system, and pairs of wires were hired from the Post Office, for use as pilots as well as for channels of communication. The scheme permitted each of the protected sections to be tapped with loads up to 400 kVA, and a minimum time setting sufficient to ensure discrimination between the main protection and the various types of switches controlling the spur lines. The use of the pilots as telephone lines did not interfere in any way with the functioning of the protective system, as under fault conditions the telephone instruments were immediately disconnected. The picking-up of intermittent stray currents on the pilots would not cause inadvertent tripping of the switches, and the open-circuiting of the pilots would merely tend to reproduce the old conditions under fuse protection where several switches might trip simultaneously. It was thought unlikely that the pilots would be out of commission on more than one section at once.

Subsequent to the adoption of the discriminating protection on the main distributors of the 11-kV network, the superimposing of a 33-kV transmission system became necessary, owing to the increasing load and the need for increased main step-up transformer capacity. The 33-kV transmission was initiated by the raising of the working pressure of an existing overhead line which had been designed for 33-kV operation from its temporary working pressure of 11 kV. It was not desired at that stage to incur the expense of installing 33-kV switchgear, and it was not proposed to incur the additional expense for pilot wires between the power station and a switching station which was already served with Post Office channels of communication. A scheme of protection was therefore sought which would cater for all faults on the step-up transformer, the 33-kV lines and the step-down transformer, as well as the 6·6-kV cables at the power station end, and the 11-kV cables from the transformer to the switchgear at the feeding point. The adoption of a fault-throwing scheme, together with Buchholz relays, earth-leakage relays and reverse-power relays achieved the desired result. In particular, it ensured that a fault on the 6·6-kV cables at the power station end would be entirely isolated and not be left connected to the 11-kV system through the 33-kV line and transformers, under which conditions an "arcing ground" might be set up, resulting in dangerous surges.

In view of the fact that the 11-kV network consisted largely of overhead lines, and since many of the faults occurring were of a transient nature, it was also decided to experiment with arc-suppression coils. To begin with, a small section of the network which was supplied by means of a step-up transformer from the end of the 6·6-kV network, and could, therefore, be readily isolated to form a separate system of its own, was provided with a small coil of 2·5 amp current-carrying capacity. This was later followed by the installation of a second coil on another section of the network, which was isolated by means of a 500-kVA 1/1 transformer, and a third small coil was installed experimentally on a section of the network which was isolated by means of a 300-kVA 1/1 transformer. The isolating transformers had been converted from their original function of 6·6/11-kV step-up transformers, and little expense was incurred in adapting them for their experimental purpose. The two additional coils were of 15 and 5 amp current-carrying capacity.

The statistical results of the improvement in continuity of supply were not very convincing, yet they gave a feeling of increased confidence to the engineers who were responsible for maintaining the supply. It was therefore decided to extend the protection, and a large coil which catered for the whole of the 11-kV network was installed in 1938. The small 5- and 15-amp coils were subsequently removed, and the two isolating transformers disconnected, so saving the iron and copper losses which their use entailed. The application of the arc-suppression coil to the whole 11-kV system involved, on the occurrence of a fault on one phase, the raising of the pressure of the two healthy phases to earth. In view of the extent of the network and the fact that much of the apparatus was not designed to operate under such conditions, it was decided that in the event of a persistent fault the coil should not be permitted to hold the potential of the faulty phase down to earth for any length of time until the fault was cleared by hand. Arrangements were therefore made to connect an earthing resistance across the coil by means of an automatic switch when a fault persisted for more than 5 sec., so that the faulty section would be isolated by the operation of the normal protective gear.

(3.3) Types of Protective Apparatus Installed

(3.3.1) Main Transmission Lines and Transformers.

The protective apparatus provided on the main 6·6/11-kV transformers consists of simple over-current and earth-leakage induction-type inverse and definite-minimum time-lag relays installed on the 6·6-kV side. Over-current protection is provided on all three phases, the earth-leakage relay being a separate unit, and intertripping connections to the 11-kV switches ensure the complete isolation of the transformers in the event of an internal fault.

The 33-kV transmission lines and their associated transformers are treated as a single unit for the purpose of protection, by adopting a fault-throwing system whereby intertripping between the 6·6-kV circuit-breaker at the generating station and the 11-kV circuit-breaker at the remote substation is effected by deliberately throwing an earth on one phase of the 33-kV system.

The arrangement is shown in Fig. 2, and it will be noted that at the generating station end of the feeder inverse time-lag over-current and instantaneous earth-leakage relays are installed on

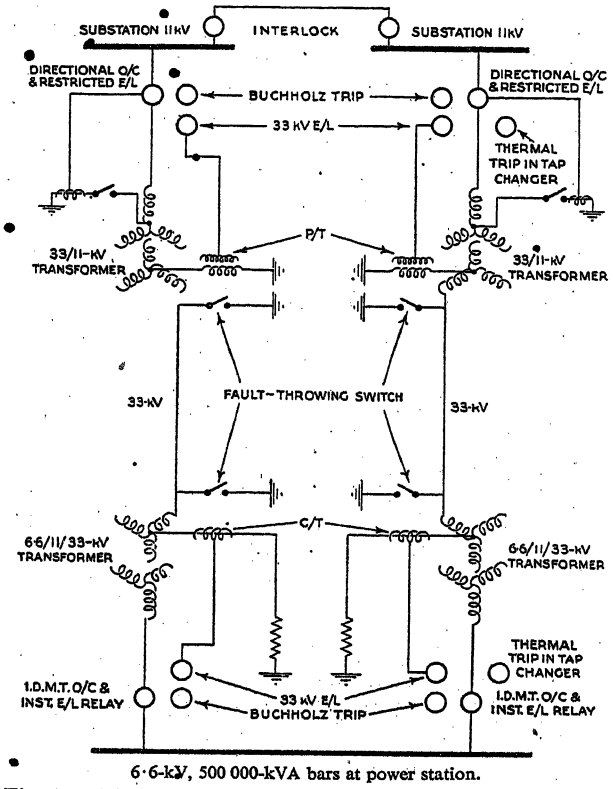


Fig. 2.—Schematic diagram of 33-kV feeder and transformer protection.

the 6·6-kV side of the transformer. The operation of either of these relays, in addition to tripping the 6·6-kV circuit-breaker, also releases a spring-operated air-break switch which earths one phase of the 33-kV winding of the transformer. On the 33-kV side of the transformer a current transformer mounted on the star-point connection which is earthed through a 50-ohm liquid resistance is connected directly to an earth-leakage relay which trips the circuit-breaker but does not operate the fault-throwing switch. A short time-delay is imposed on this relay to avoid operation due to transient faults.

At the substation end, directional over-current and restricted earth-leakage relays are installed, and between the star point on the 33-kV winding of the transformer and earth a single-phase voltage transformer is connected. The secondary winding of this voltage transformer is connected to an earth-leakage relay. A fault-throwing switch similar to the one at the generating station is operated by the directional and restricted earth-leakage relays only.

Earth faults on the 33-kV line are cleared by operation of the earth-fault relays connected on the 33-kV side of the transformers, operating current being provided respectively by the neutral-current transformer and by the raising of the potential of the star point of the transformer at the substation end.

Phase faults on the 33-kV line and phase or earth faults on the 6·6-kV and 11-kV switchgear and connecting cables are dealt with by the over-current and earth-leakage relays, intertripping between the circuit-breakers being effected by the fault-throwing switches, thus ensuring the complete isolation of the fault. In addition the transformers themselves are protected by means of Buchholz relays provided with both gas and surge floats. Operation of the gas float by gradual accumulations of gas causes visual alarm to be given by an indicator at the substation in the case of the substation transformers, and audible alarm at the power station in the case of the power-station transformer. The surge float, which would be operated by the sudden giving off of gas in the case of an internal fault on the transformer, causes the adjacent 6·6-kV or 11-kV oil circuit-breaker to trip instantaneously, and at the same time operates the 33-kV fault-throwing switch, so bringing out the remote oil circuit-breaker and completely isolating the particular feeder.

This system has been found to give excellent results in practice, and burning of the fault-throwing switch contacts has been found to be very slight.

(3.3.2) **11-kV Main Distributors.**

The two 11-kV radial feeders are both tapped along their route and are, therefore, in reality 11-kV distributors. These two feeders, together with 8 sections of the main ring, are now operated as an interconnected circuit. Ten of the sections of the ring thus formed are equipped with "Interlock" protection, the remaining sections being protected with inverse-time over-current relays. Back-up protection is provided by over-current relays at a number of points on the ring. These have fairly long time-delays and serve merely to guard against failure of the interlock protection and faults outside the zone of the feeder protection.

The remaining sections of the circumferential ring are kept sectionalized and protected by inverse definite-minimum time-lag over-current relays.

The general arrangement of the protection on the 11-kV system is shown in Fig. 3.

The principle of the interlock feeder protective system is based on a comparison of the direction of a fault current at either end of a feeder. If a fault current flows into one end of a protected section of a ring main and at the same time flows out of the section at the other end, then that section must be healthy and the protective relays must be prevented from operating and isolating the circuit by means of a stabilizing impulse or signal transmitted along pilot lines to the opposite end. If, however, fault current flows in opposite directions at the two ends, the feeder is faulty, and as no stabilizing signal is transmitted under

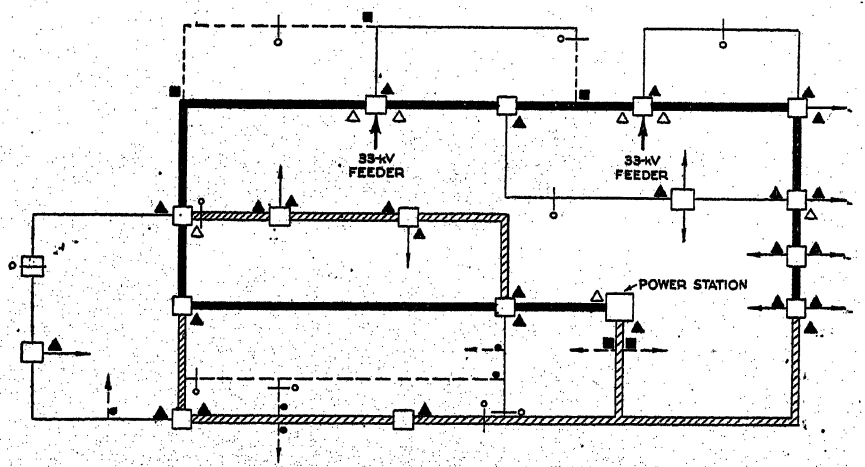


Fig. 3.—Schematic diagram of 11-kV system protection.

these conditions the protective gear trips the oil circuit-breaker. The relays, comprising the equipment at each end of the protected section, include:—

(*a*) A two-stage non-directional phase-fault relay.
(*b*) A directional relay.
(*c*) An earth-leakage relay.
(*d*) An auxiliary operating relay.
(*e*) An auxiliary stabilizing relay.
(*f*) A lock-out relay.
(*g*) A definite time-lag or hesitation relay.

The occurrence of a fault operates the first stage of the 2-stage over-current or earth-leakage relay. This operation applies potential to the directional relays, the contacts of which open when current flows into the feeder and close when it flows out. If the contact remains closed the stabilizing relay operates, the telephone is disconnected and the 30-volt insulated battery is connected across the pilots to send a stabilizing signal. If the contact of the directional relay opens, the operation of the second stage energizes the operating relay which, in turn, starts the time-hesitation relay, but in addition it connects the lock-out relay across the pilots. If a stabilizing signal has been transmitted from the remote end, operation of the lock-out relay takes place, the time-hesitation relay circuit is de-energized, and the circuit-breaker remains closed.

In the case of a fault on the protected feeder, current flows into the feeder from each end; this opens both of the directional relay contacts and allows complete operation of the over-current or earth-leakage relays. No stabilizing signal is transmitted as neither stabilizing relay is energized, and after the interval provided by the time-hesitation relay both circuit-breakers are tripped.

When the fault is in a section other than the protected section, the directional relay contacts will open at the end of the feeder at which current flows into the feeder, and close at the opposite end. These operations result in the operating relay being energized at one end and the stabilizing relay being energized at the other. A stabilizing signal is thus transmitted from the far end of the feeder where the circuit-breakers will not trip because the operating relay has not been energized, is received by the lock-out relay at the near end, de-energizes the time-hesitation relay, and prevents the tripping of the circuit-breaker.

In the equipment first installed, the time-hesitation relay was of the definite-time type, but in later installations this is omitted and the second-stage over-current or earth-leakage relay is of the induction-disc pattern, giving a delay having an inverse time characteristic with a definite minimum time-lag.

Post Office pilot wires are used for conveying the stabilizing impulses from one end of a section to the other in the majority of sections, but in two sections, where the main line consists of underground cable, pilot cables have been laid by the Corporation.

The use of Post Office pilots necessitates special precautions to prevent dangerous or harmful potentials getting back to the Post Office system under fault conditions. This is accomplished by separating the operating coils of the relay from the contacts with insulating barriers which must be capable of withstanding 15 kV momentarily and 5 kV for 2 minutes.

Where the pilots are owned by the Corporation the high degree of insulation is unnecessary, and the whole of the equipment is considerably simplified in consequence.

The equipment also includes fault indicators and a lock-out relay-operation counter, indicating the number of straight-through faults dealt with by the equipment. Fig. 4 shows the connections for the "Interlock" system of protection.

(3.3.3) **11-kV Subsidiary Distributors and Spur Lines.**

Subsidiary distributors radiating from the section points on the ring main or from the terminal points of the 33-kV main transmission lines or e.h.v. feeders are protected by induction-type inverse definite-minimum time-lag relays.

Spur lines are protected by oil circuit-breakers fitted with series coils or fuses of the carbon-tetrachloride type and sometimes are even connected direct to the e.h.v. distributor, depending on the location, length and importance of the particular line. Some of the oil circuit-breakers are of the automatic-reclose type, but the installation of this class of switch has been generally retarded by war-time economic considerations.

On certain spur lines considerable lengths of overhead construction have been replaced by underground cable. These spur lines usually have small transformers varying from 10 kVA to 50 kVA connected to them, and it has been found that where such lines are protected by tetrachloride-type fuses the blowing of one fuse due to a single-phase fault results in an abnormally high voltage appearing across the secondary of the transformers, particularly when they are lightly loaded. This abnormal voltage may be as much as 50 % in excess of normal, and is due to voltage resonance between the cable capacitance and the transformer inductance. This may be explained by considering the circuit to be reduced to an inductance and capacitance in series. If an alternating voltage is applied across this circuit and gradually raised in value, at a certain critical voltage dependent on the inductance and capacitance values of the circuit, resonance will suddenly take place, resulting in an abnormal increase in current and a corresponding abnormal increase in voltage across the inductance. It so happens that in certain of the spur lines mentioned, the values of the cable capacitance and transformer inductance are suitable for resonance at about the phase-to-neutral voltage of the system. It has therefore been necessary to adopt a means of protecting these lines which will ensure that on the occurrence of a fault all three phases are interrupted simultaneously. This protection usually takes the form of a pole-mounted oil switch.

(3.3.4) **Distribution Transformers.**

The individual substations, mainly consisting of pole-mounted equipment, are protected by fuses, with a few exceptions where the transformer is connected direct to the line. This practice has only been adopted on short spur lines where a number of substations are relatively closely grouped, the group being treated as a whole for the purpose of protection. On many of the older substations the fuses are of the rewireable type, but all those erected during the last few years are of the tetrachloride type. It has been found necessary to pay special attention to the type of fuse-holder employed, as experience has shown that with the superimposing of the 33-kV transmission system on the network, and the consequent increase in available short-circuit kVA, certain types of spring-clip holders, even if provided with safety catches, are not strong enough to retain the fuses against the mechanical forces set up by the short-circuit currents. In positions near to the 33-kV feeding points a type of holder employing roller contacts which firmly grip the ends of the fuses has been found more satisfactory than the spring-clip type.

(3.3.5) **Arc-Suppression Coils.**

An arc-suppression coil is designed to prevent a power arc following a transient fault by neutralizing the capacitance of the network. The coil, which is connected between the neutral point of the system and earth, has an inductance such that on the occurrence of an earth fault the reactive current caused to flow through it by the potential of the neutral point which is raised to phase voltage is equal and opposite to the sum of the capacitance currents of the two sound phases. Theoretically, therefore, the current in the fault and the voltage difference between the fault and

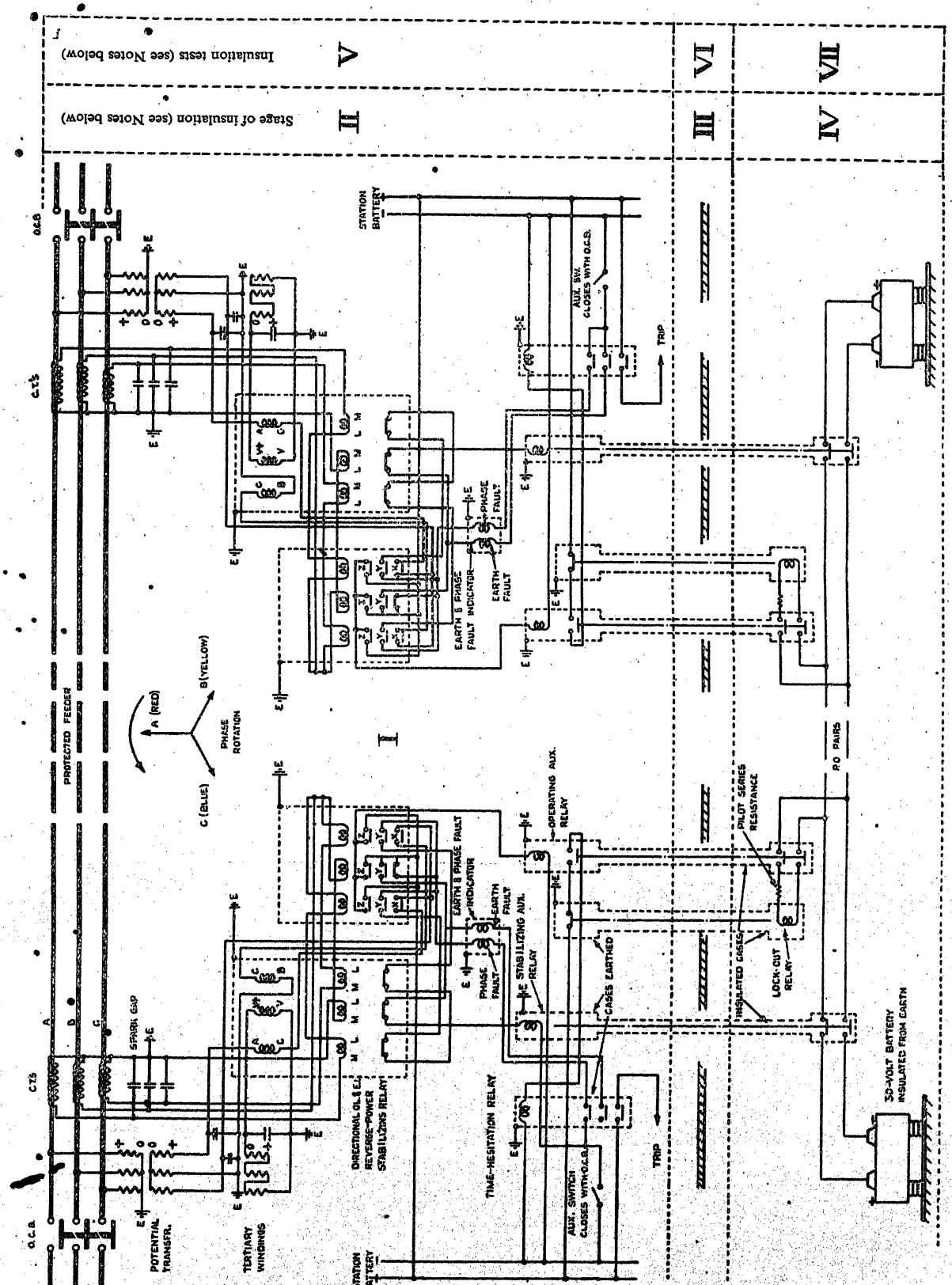


Fig. 4.—Diagram of connections of interlock protection using P.O. pairs and physically separated relays.

NOTES.—I. Two-stage O.L. and E.L. relay. Contacts X and Y bridged at a low fault-current setting. Contacts X, Y and Z bridged at a higher fault-current setting. II. Earthed enclosure. III. Physical separation of relay parts with insulating barrier between coils and contacts. IV. Physically separated stage. Insulated enclosure. V. The following parts to withstand the appropriate B.S. test pressure to earth, namely 2 000 V for 1 min, transformer l.v. windings, relay coils and contacts, circuit-breaker auxiliary switches, wiring. Cases and metal parts to be earthed. Protected spark gaps to break down at 400/750 V. Wiring run as in standard practice. VI. Between coils and contacts 15 kV momentarily; 5 kV for 2 min. VII. Wiring to be of 2 200-V grade cable run on insulated cleats. All parts, including wiring, to withstand P.O. test pressure to earth of 15 kV momentarily and 5 kV for 2 min.

earth will be reduced to zero, but in practice there will remain a small residual current in the arc, due to losses and leakages in the reactor and lines. If the fault is of a transient nature this will not be sufficient to maintain the arc. To clear a persistent fault, a normal earthing resistance may be switched in after a short time-delay.

The coil is provided with tappings for tuning purposes, and the selection of the best tapping is carried out by measuring the current in the neutral under normal conditions. When the coil is most nearly in tune, i.e. nearest to a resonant state, out-of-balance on the network will appear to reach a maximum value. Thus the highest value of neutral current recorded indicates the best tapping to use. Once the coil has been initially tuned, it is only necessary to make an occasional test to ensure that a reasonable degree of tuning has been maintained, and unless the characteristics of the network have altered little further attention should be necessary.

The occurrence of a fault is indicated on a recording instrument connected across a secondary winding on the arc-suppression coil; and, if another recorder is connected across a current transformer slipped over the earth-resistance connection, a comparison of the charts will indicate transient faults cleared by the coil and those permanent faults which have to be cleared by the operation of the normal protective gear.

Table 3

TESTS ON ARC-SUPPRESSION COIL

Test number	11	15	17	35	36
Type of fault ..	2-in gap over insulator bridged by 10-amp fuse wire. Red phase	1½-in gap over insulator bridged by 10-amp fuse wire. Red phase	1½-in gap over insulator bridged by 10-amp fuse wire. Red phase	Solid. Red phase	Solid. Red phase
Suppression coil tapping number	5 Optimum value (162 amp)	7 + 29·6% optimum value	1 − 35·2% optimum value	5 Optimum value	7 + 29·6% optimum value
Fault current ..	190 amp (max. inst. value)	Variable	250 amp (max. inst. value)	30 amp (steady value)	50 amp (steady value)
11-kV neutral voltage	6·0 kV	4·5 kV	6·35 kV	6·35 kV	6·35 kV
Clearing of faults ..	Slight arc cleared quickly after 4 cycles	Small arc clearing after 1 cycle	Small flash arc cleared after ½ cycle	Fault cleared by hand after 57 cycles	Fault cleared by hand after 88 cycles
Effect on network ..	Network oscillates considerably before settling to normal	Slight oscillations on network. Normal after 7 cycles	Pronounced oscillations on network, lasting about ½ sec	Fault kept suppressed	Fault kept suppsuppressed
Oscillogram Nos. (see Fig. 5)	—	15c and 15t	17c and 17t	—	36c and 36t
Operation	Correct	Correct	Correct	Normal	Normal

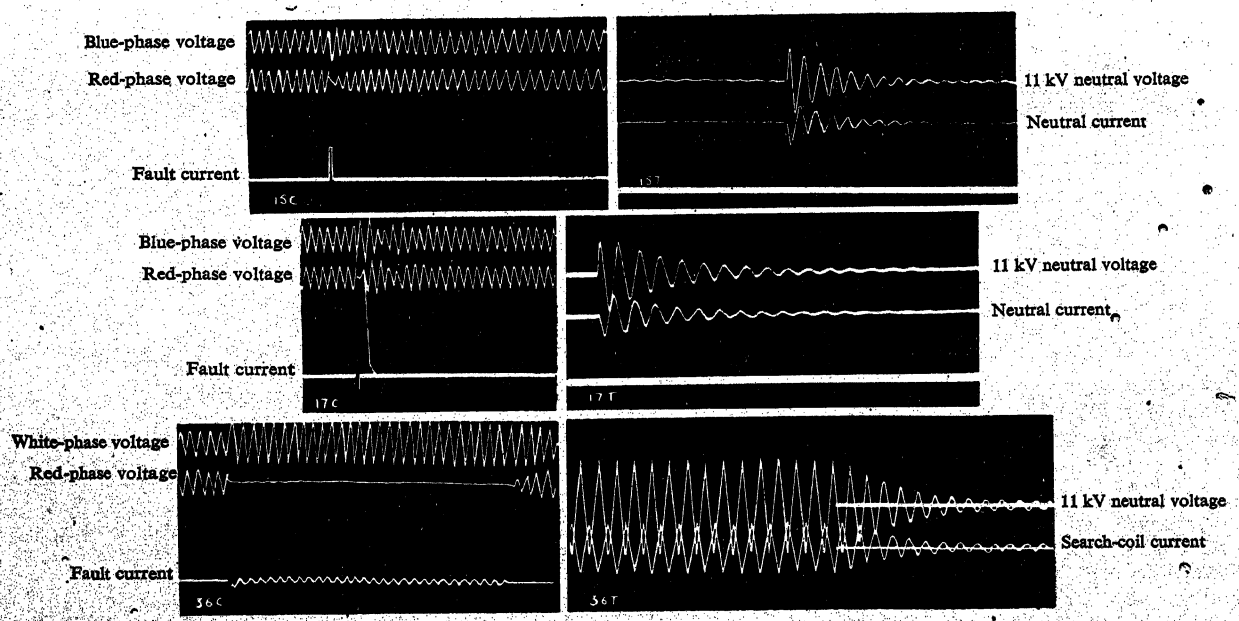


Fig. 5

A series of tests was carried out on the coil installed to protect the whole of the 11-kV network under review. These tests included observations of the operation of the coil in clearing arcs struck across insulators, and measurements of the residual current in permanent faults. Samples of results are given in Table 3 and reproductions of oscillograms in Fig. 5. These tests show that satisfactory operation is obtained over a wide range of adjustment.

(3.4) Operation and Maintenance Difficulties

Protective gear, unlike most electrical gear, is inactive for the major portion of its life, but it must be in a condition to come into operation at the very instant required. It is therefore of the utmost importance that efficient maintenance be carried out to ensure that relays and operating coils are kept free from dust, rust or other corrosion which would result in moving parts becoming sticky or sluggish in action. Contacts must be kept clean, and steps must be taken to see that tripping batteries are always fully charged. In addition to frequent cleaning on site, it is desirable to change the relays at intervals of about three years so that they may have a complete overhaul and inspection in the test room.

Routine tests may be carried out by secondary injection, but, wherever possible, primary injection, which brings the current transformers within the range of the test, should be carried out at intervals.

This testing of protective gear should occupy the whole time of a competent engineer on supply networks of any size, but very often the work has to be undertaken as a side-line by an engineer engaged on other duties, with the result that it is often neglected.

Maintenance of protective gear is even more difficult in rural areas than in urban areas, chiefly owing to the distances between substations and the time taken in travelling between them. It is therefore necessary to take exceptional precautions to see that protective apparatus is not affected by dampness, and it has been found helpful to provide slight local heat in the neighbourhood of relays and trip coils in substations and kiosks. This is usually done by short lengths of tubular heater installed in a convenient position below the apparatus.

Time-lag fuses have been a source of trouble, owing to the deterioration of the fuse wire or corrosion of contacts. No attempt is made to secure discrimination by time-lag fuses as this has been found unreliable. This time-lag fuse is only used to prevent operation due to momentary disturbance on the system.

The changing of trip batteries for recharging has been made unnecessary by the installation in all rural substations of trickle chargers with metal rectifiers. This has eliminated a considerable amount of labour and ensures that the batteries are always in a fully-charged condition. Topping-up and general inspection is carried out when the protective gear is inspected.

A difficulty in operation which has caused considerable trouble on the system described is the failure of pilots which are rented from the Post Office. This results in a failure of the protective gear to stabilize on through-fault currents, and causes healthy sections of the network to be tripped out unnecessarily. A system of automatically testing the pilots every half-hour has been used, and in the event of the alarm sounding it is necessary to travel round the main ring to determine which section is faulty. In spite of the excellent service normally given by the Post Office maintenance staffs, there have been periods when the pilots were out of commission for some time. Another factor is that very often the cause of a fault on the power system also puts the pilot circuits out of use, particularly on overhead circuits; underground circuits have been found exceedingly reliable.

Observation of the operation of protective gear is most important so that records can be kept and inadvertent operation investigated. The latter can only be carried out if the mains engineers take careful note of the indicators on the relays before resetting when they are actually dealing with a fault The general tendency seems to be that they are so anxious to get the supply restored that observations have frequently been neglected, and it has been necessary to insist that attention be paid to this matter even though it results in a small extension of the time of interruption of supply.

(3.5) Records of Faults

Checking the operation of a protective system is closely connected with the recording of the actual faults which have occurred, and, in addition, remedial measures which experience dictates need to be applied to the system come under the general heading of protection.

It is therefore proposed to describe the system which has been evolved to classify and obtain statistics relating to faults of different types. Faults are classified and numbered under the following headings:—

A. *Overhead line faults.*
   (1) Special causes due to abnormal conditions.
   (2) Birds.
   (3) Trees.
   (4) Insulation failure.
   (5) Lightning.
   (6) Mechanical failure.
   (7) Unclassified.

B. *Cable faults.*
   (1) Joints.
   (2) Pole boxes.
   (3) Mechanical damage.
   (4) Unclassified.

C. *Switchgear faults.*
   (1) Electrical.
   (2) Mechanical.

D. *Transformer failures.*

E. *Faults due to unknown causes.*

F. *Faults due to enemy action.*

G. *Faults which do not come under any of the above headings.*

Many of the above classes can occur on either the e.h.v. or l.v. systems and indication is given, e.g. a fault caused by a bird on the e.h.v. system would be classified as E.H.V./A(2).

The best indication of the extent of an interruption due to a fault is given by the number of consumer-hours lost, but to obtain this information a great deal of computation is involved, and it is found simpler to use the number of substation hours interruption as a guide. This figure is, in general, easily obtained from the records of switching times and forms a useful comparative basis.

Table 4 gives for the past three years the figures for faults on the e.h.v. network described above.

The analysis is extended in a similar manner to cover the central urban areas and also faults on the l.v. system. A further comparison on a district basis is prepared each year on the lines shown in Table 5. This Table, which is used to assess the percentage of continuity of supply, includes l.v. faults as well as e.h.v. faults.

Table 6 gives the total summary of rural-area faults on the e.h.v. and l.v. systems, extending over a number of years.

Examination of a fault analysis set out on the lines suggested immediately reveals the types of fault which are causing the

Table 4

ANNUAL FAULT ANALYSIS

Classification (see page 17)	1939			1940			1941		
	No. of faults	Substation-hour interruptions	Substation-hours per fault	No. of faults	Substation-hour interruptions	Substation-hours per fault	No. of faults	Substation-hour interruptions	Substation-hours per fault
A(1)	13	1 128·16	86·8	46	3 341·5	72·7	6	425·87	70·84
A(2)	10	97·1	9·7	9	129·0	14·3	10	123·02	12·3
A(3)	6	118·18	19·7	12	515·7	42·9	4	36·72	9·18
A(4)	10	468·87	46·9	17	353·5	20·8	9	284·82	31·65
A(5)	122	1 975·08	16·2	36	844·8	22·5	19	215·71	11·32
A(6)	—	—	—	8	70·6	8·8	5	200·0	40·0
A(7)	1	32·8	32·8	3	100·3	33·4	14	500·86	35·7
B(1)	—	—	—	9	262·5	29·5	3	42·4	14·13
B(2)	3	106·5	35·5	7	289·0	41·3	11	1 189·39	108·13
B(3)	—	—	—	—	—	—	2	32·5	16·25
B(4)	2	43·3	21·7	—	—	—	—	—	—
C(1)	4	59·11	14·8	10	711·2	71·1	14	598·0	42·7
C(2)	—	—	—	2	77·7	38·9	—	—	—
D	2	14·66	7·3	1	16·1	16·1	3	12·23	4·06
E	31	265·98	8·6	45	1 416·0	31·5	25	719·29	28·8
F	—	—	—	1	113·6	113·6	7	490·47	70·07
G	1	12·5	12·5	5	203·7	40·7	9	92·18	10·24
Totals	205	4 322·24	21·1	211	8 445·2	40	141	4 963·46	35·2

Table 5

DISTRICT FAULTS SUMMARY—1941

District	No. of faults	No. of substations in district	Substation interruptions	Average substation interruptions per fault	Substation-hour interruptions	Average substation-hour interruptions per fault	Average duration of fault, hours	Per cent continuity of supply
Eastern ..	113	328	1 423	12·60	2 705·96	24·22	1·92	99·90
Western ..	55	326	1 167	21·20	2 268·31	41·2	1·94	99·92
Central ..	15	96	42	2·80	101·48	6·76	2·41	99·98
Totals ..	183	750	2 632	13·8	5 075·75	27·70	2·0	99·92

Table 6

ANNUAL FAULTS SUMMARY

Year	1936	1937	1938	1939	1940	1941
No. of faults	136	115	180	214	242	183
Substation interruptions ..	3 146	1 558	2 909·4	3 458·5	4 735·9	2 632
Substation-hour interruptions	2 037	2 661	2 310·5	6 153·7	8 542·2	5 075·75
Per cent continuity of supply	99·96	99·95	99·96	98·89	99·85	99·92

greatest interruption of supply. This may not always be the one that shows the greatest number of actual faults, but it takes into account also the time required for repair and complete restoration of supply. The preventive action to be taken may be considered as a part of the protection of the system, and matters that have and are receiving attention are indicated.

(3.6) Preventive Measures—Applied and under Consideration—for Reducing the Number of Faults

(3.6.1) Arc-Suppression Coils.

In the early years of rural supply it was found from the fault analysis that the greatest outage due to any one cause was that occasioned by lightning, and as a consequence the arc-suppression coil, previously described, was introduced to protect the whole 11-kV system.

Table 7 shows the effect of the coil which was connected in 1938.

From the statistics for the past three years it will be noted that, apart from the large increase in the first year of working, probably due to weak spots being overstressed, faults due to lightning have been considerably reduced, but these still remain one of the greatest single sources of trouble. The installation of the coil has, however, greatly reduced the amount of damage to apparatus following flashovers due to lightning. Examination of the

INTERRUPTION OF SUPPLY.

Report No.....
Part A.
To be sent to Head Office within 24 hours of occurrence.

The supply to.....

.....

was interrupted from.....on.....194 , to.....on.....194 .

Substation interruptions ..... Duration.....

Notice sent to Electricity Commissioners (if necessary) Date .....

General description of interruption.....

.....

.....

.....

.....

.....

.....

.....

Date..... Signed.....

District Engineer

FOR HEAD OFFICE USE Date received.....

Report examined by	Initialled	Date
Mains Superintendent		
Technical Assistant		
Deputy City Electrical Engineer		
City Electrical Engineer ..		

Reported to..... Date.....
(Factory Inspector or other Govt. Dept. when necessary)

Filed..... Initial.....

INTERRUPTION OF SUPPLY.

Report No.....
Part B.
To be sent to Head Office within 7 days of occurrence.

Time and date of fault..... Classification of fault.....
Time first report received..... From .....
Place of occurrence.....
Cause of interruption.....
Material damage caused.....
Type of equipment ..... Date erected or jointed.....
Phase or phases involved.....
Switches which cleared fault:

	Substation.	Switch.	Type of relay or trip fuse.	Flag indication.
1.				
2.				
3.				
4.				

		No.	Duration	Substation-hours.
Substations interrupted by automatic tripping of switches ..	1.			
	2.			
	3.			
Substations interrupted by switching operations necessitated for localization or repair ..	1.			
	2.			
	3.			
	Total ..		Total ..	

Weather conditions at time of fault.....
Steps already taken to repair fault.....
.....
Remarks and suggestions for prevention of similar occurrences in future.....
.....
.....
Signed.....
District Engineer.

Observations on above.....
.....
Signed.....

Action to be taken.....
.....
Signed.....

FIG. 6

Table 7

Year	Number of lightning faults	Substation-hour interruptions
1935	77	1808
1936	58	892·3
1937	60	1328·96
1938	61	359·80
1939	122	1975·08
1940	36	844·8
1941	19	215·7

individual report indicates that the main trouble now experienced is due to blown fuses, and it is possible that the large residual current in a fault which results from the use of a single coil only on so extensive a system may be a contributory factor in producing this effect. Further improvement might be obtained by splitting up the network into sections, each protected by a separate coil.

It should be mentioned that the characteristics of the network have been changed very appreciably since the installation of the coil, owing to a considerable increase in the mileage of underground cable, and that the range of tappings on the coil is no longer sufficient for tuning purposes. The installation of further coils to remedy this condition is now being considered.

(3.6.2) **Earth Wires.**

Experience has proved the value of the screening effect of overhead earth wires placed above the conductors as protection against lightning. They are installed on all new main lines on the system, but are omitted on spur lines on the ground of economy.

(3.6.3) **Lightning Arresters.**

It is very difficult to assess the usefulness of lightning arresters, as observed results give only negative evidence. Horn gaps are no longer used owing to their doubtful value and the possibility of the steep-tailed wave which their operation leaves on the line causing trouble on transformer windings and terminal apparatus. It is, however, proposed to install at the earliest possible opportunity Thyrite-type arresters at positions where main lines are connected to underground cable sections, in order to protect the pole boxes, cables and terminal apparatus connected to the other end of the cables.

(3.6.4) **Insulation of System.**

Insulation failures have been chiefly due to damage by stone-throwing or gun-shot, brine deposit and ageing of strain insulators and 2-piece pin insulators. No ageing has been noticed in pin insulators made in a single piece.

Sections on which frequent insulation failures have been noted are being dealt with by replacing those types of insulators subject to ageing, and by removing the earth connections from the steel cross-arms on wood-pole lines in cases where a higher insulation value of the system is considered desirable.

(3.6.5) **Pole Boxes.**

The increase in the number of pole-box failures on the system has become alarming, and an analysis of this item shows that the great majority are due to two types of boxes erected in the early days of rural supply. This was due partly to the design of the boxes and partly to the method of installation adopted at that time, jointing having been carried out at ground level and the box lifted into position afterwards. The resulting movement of the cable cores placed the solid compound under severe stress, causing cracking and eventually leading to failure.

It has therefore been considered expedient to embark on a programme of replacement of these boxes before further failures occur.

(3.6.6) **Switchgear Failures.**

The majority of switchgear failures have been due either to open-type current transformers installed in kiosks or to the deterioration of air-break switchgear. The former have been replaced by compound-filled types, and a survey of the existing overhead-line switchgear has been prepared so that replacement of equipment in bad condition can be made as opportunity occurs.

(3.6.7) **Transformer Bushings.**

At one time the bushing insulators fitted to pole-mounting transformers were a frequent cause of trouble. This matter was investigated in conjunction with the manufacturers, the design modified, and the insulator so arranged that any flashover would take place from the stem to the tank. Insulators on all existing transformers were changed, and since this has been done there have been very few further failures.

(3.6.8) **Mechanical Failures.**

Mechanical failures have been chiefly conductor failures due to electro-chemical corrosion in composite conductors, particularly steel-cored copper. Cadmium-copper or plain hard-drawn copper is being used for all new lines.

(4) A STANDARD FORM FOR RECORDING FAULTS

In order that useful analyses may be prepared it is essential that very full reports be made relating to every fault. To prevent the omission of necessary information, a standard form is used. This consists of two parts, one giving preliminary details to be sent in within 24 hours of the occurrence, and the other to be returned within 7 days, giving final details. The latter period is allowed to permit of line patrols and full investigation of the occurrence.

The type of fault report is indicated in Fig. 6, and it is suggested that this form, modified if necessary to make it universally applicable, together with the method of classification detailed in Section 3.5, might be adopted as standard by supply undertakings. The preparation of fault statistics would then be simplified and different undertakings would be able to compare the incidence of faults on their networks.

At the present time, undertakings can only compare one year's operation with another and have no means of telling whether their standard is good or otherwise.

The authors would even go so far as to suggest that the provision of returns relating to e.h.v. faults should become obligatory in the same way that returns are required for specified occurrences under the Factory Acts and the Commissioners' Regulations. These returns should be sent to some technical body who would carry out the work of correlation and make the information available to the supply industry in general.

ACKNOWLEDGMENTS

The authors desire to acknowledge their indebtedness to the City Electrical Engineer and Electricity Committee of Norwich, also to Messrs. A. Reyrolle and Co., Ltd., for permission to publish certain of the information and diagrams included in this paper, and to a number of colleagues who have made helpful suggestions.

IV. AUTOMATIC SELECTIVE ISOLATION OF SUSTAINED EARTH FAULTS ON A NETWORK PROTECTED BY PETERSEN COILS

(*The paper was first received 20th March, 1942, and in revised form 3rd March, 1943.*)

SUMMARY

This paper explains what is believed to be a unique method evolved for protection of a grid network of 37·5-kV transmission lines against line-to-earth faults, which enables automatic selection and isolation of a section subjected to a sustained fault to take place without utilizing earth-fault current for the operation of protective relays, or pilot wires between sectionalizing stations remote from one another.

The scheme provides for the installation of Petersen coils together with special automatic selectors and associated equipment, and has been employed with considerable success since 1936 for protection of the Ganges Canal hydro-electric grid in the United Provinces, India.

(1) GENERAL

(1.1) Brief Description of the Undertaking

The Ganges Canal grid has been developed from three small independent hydro-electric power supply schemes instituted by the United Provinces Government in 1928–29.

The primary object is to supply power over a wide area in the Western Districts of the Provinces at an economic figure to enable the population in rural tracts to develop hitherto uncultivated land for agricultural purposes with the aid of water pumped electrically from the subsoil. The network of supply now extends over 13 000 square miles, and 4 300 miles of overhead line, which includes the 11 000-volt and 400-volt subsidiary rural lines, is in commission. Some 88 towns and villages within this area are also supplied with electricity for domestic and minor industrial purposes.

Power is derived from a chain of 7 hydro-electric stations situated on falls along the Ganges Canal, which was constructed purely for irrigation purposes during the last century. During periods of maximum canal discharge a total of 18 000 kW may be generated, and in order to meet a peak of 25 000 kW which occurs during certain months of the year a peak-load and standby steam station of 9 000 kW capacity has been constructed at a strategic point on the grid.

(1.2) The 37·5-kV Grid

The entire 37·5-kV grid network protected by the scheme consists of conductors supported on pin-type insulators fitted to channel-iron cross-arms.

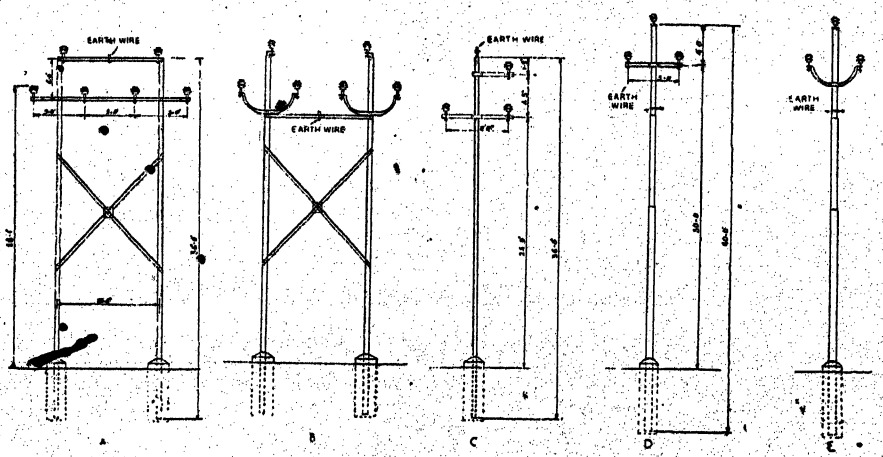


Fig. 1.—Types of double-circuit and single-circuit lines.

A. Original type of double-rail structure.
B. Double-rail structure with modified cross-arms.
C. Single-circuit rail structure.
D. Single-circuit pole structure.
E. Single-circuit structure with "U" cross-arm.

The original cross-arms were of the straight horizontal pattern; in recent years these have been modified to a "U" shape in an attempt to prevent interference from birds. Fig. 1 shows the original and modified designs of single-circuit and double-circuit structures.

Fig. 2 shows the arrangement of the 37·5-kV system, together with power stations and sectionalizing points, in operation at the time the automatic selective scheme was introduced. This diagram also indicates the stations at which Petersen coils, selectors and potential transformers have been installed. Power stations at Bahadrabad, Bhola, Palra and Sumera only were in commission and the system was operated as a closed circuit. For the sake of clearness intermediate step-down substations connected to the lines between sectionalizing points have been omitted from this diagram. With the exception of the sectionalizing point at Hapur all breakers are fitted with electrically operated closing mechanisms of the motor-driven centrifugal pattern.

The original form of protection employed was of the usual overload and earth-leakage pattern operating in conjunction with definite-time relays. Reverse-power relays were installed at Roorkee on the two incoming circuits from Bahadrabad, on the double circuit at Bhagwara, and on the incoming line from Bhagwara at Moradabad, as no power was required to flow northwards from these points.

Shortly after the grid was commissioned in 1930 it became apparent that the number of outages being experienced due to line faults was very much higher than had been anticipated, and in fact as many as 60 interruptions a month were recorded on certain sections of the system. The majority of these were of short duration and it was usually possible to reclose a breaker immediately after it had tripped. Much time was devoted to a detailed investigation into the causes of outages, and results indicated that over 90% were due to temporary line-to-earth faults, the origin of which was definitely traced to interference by large birds. Experiments with different types of bird guards designed by this Department were conducted, by means of which interference was reduced, but not to the desired extent.

Apart from annoyance caused to consumers by these interruptions, each fault was accompanied by a heavy "kick" on the power stations due to the operation of overload and earth-leakage protective gear being dependent upon fault current. Owing to the high-speed regulation of the type of water-turbine sets employed and to the fact that high-speed excitation of the machine exciters had not then been introduced in the stations, faults sometimes caused incorrect relay operation and the stations to fall out of synchronism.

The experiments with bird guards having effected only a partial remedy, a Petersen coil capable of protecting 50–100 miles of single-circuit line was installed for experimental purposes in 1933 on the section of line between Sumera and Agra.

(1.3) Installation of Initial Petersen Coil

The experimental coil, which has since been incorporated in the final scheme, is of the 3-limbed pattern and ranged 9·9–18·2 amp adjustable in 20 steps. A built-in current transformer (ratio 20 : 5) is provided in the primary winding for operating a recording

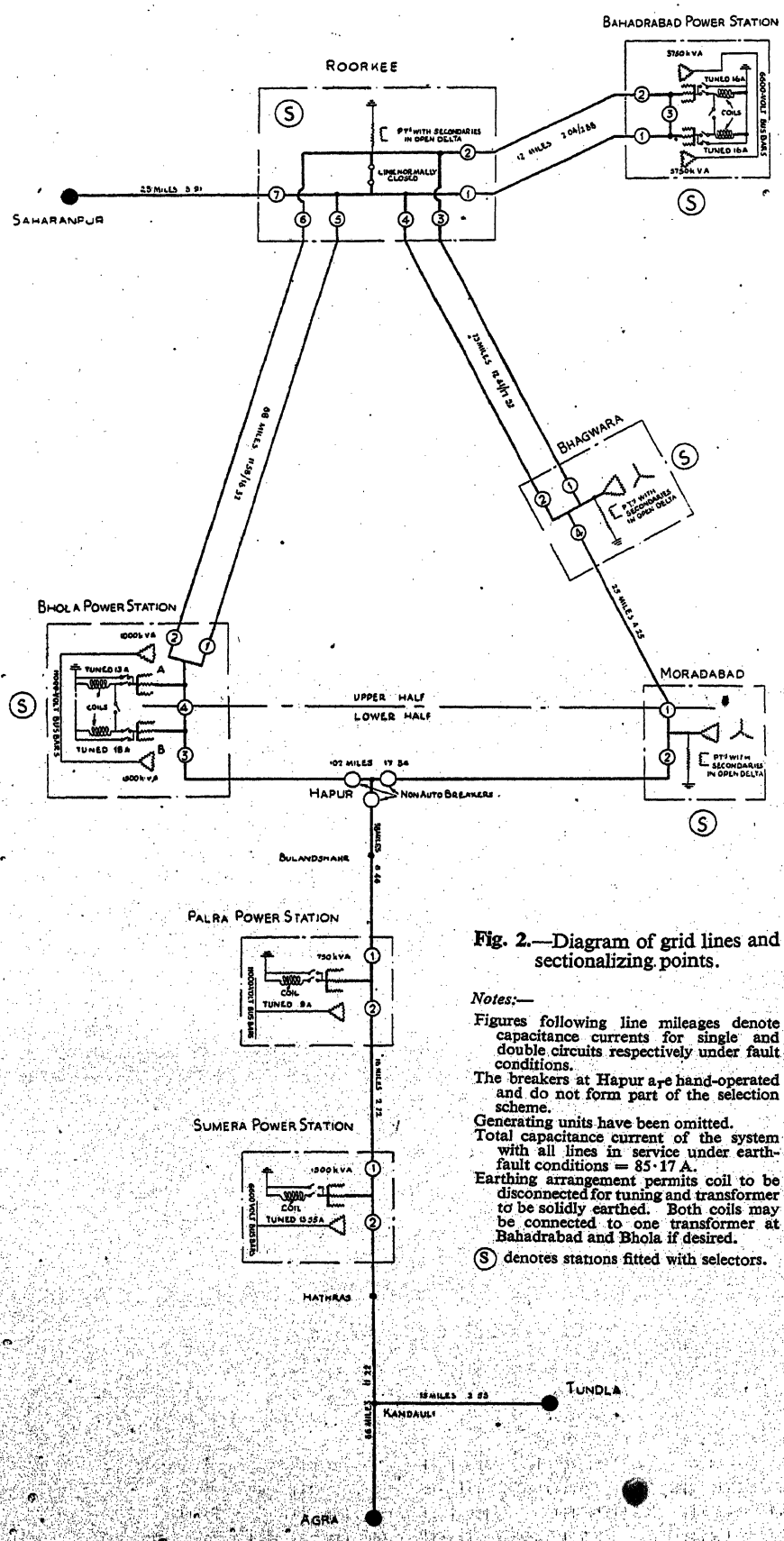


Fig. 2.—Diagram of grid lines and sectionalizing points.

Notes:—

Figures following line mileages denote capacitance currents for single and double circuits respectively under fault conditions.
The breakers at Hapur are hand-operated and do not form part of the selection scheme.
Generating units have been omitted.
Total capacitance current of the system with all lines in service under earth-fault conditions = 85·17 A.
Earthing arrangement permits coil to be disconnected for tuning and transformer to be solidly earthed. Both coils may be connected to one transformer at Bahadrabad and Bhola if desired.
(S) denotes stations fitted with selectors.

ammeter, and a low potential may be obtained from a winding tap when the coil is subjected to neutral-point voltage. From curves showing measured values of capacitance current to earth in amperes per kilometre of line for similar lines then in operation on the Continent, and from a mathematical theory developed by the manufacturers, it was expected that the capacitance current to be neutralized would be approximately 0·18 amp per mile.

The coil was installed at Sumera power station and connected between the star point of the 1 500-kVA, 37·5-kV transformer winding and earth. Whilst tuning the coil to various sections of the Sumera–Agra line, a careful watch was kept on the behaviour of the turbo-alternator sets before and during application of an artificial earth through a resistance. Readings of busbar voltage, load current, excitation voltage and current were compared and found not to vary, and no "kick" on the power station was experienced on application of the artificial fault. The earthing resistance was removed and earth faults were applied direct to the line through 3-amp fuse-wire stretched across a 20-in gap, the circuit being complete with an isolating switch. The gap was gradually reduced and the minimum restriking distance found to be only 2 in.

A method in general use for disconnecting a line under sustained earth fault is to short-circuit the Petersen coil either directly to earth or through a resistance after a definite time-interval to permit earth-fault current to flow and operate protective relays.

As the experiments showed that on the application of a fault to the line no "kick" was produced in the power station, it was considered more desirable to arrange for the isolation of sustained earth faults to be accomplished without earthing the system. A current relay (the only type available) was therefore connected in series with the recording ammeter and arranged to work in conjunction with a definite-time relay set at 7 sec, after which the controlling breaker would trip.

The coil was put into service to protect the Sumera–Agra section on the 19th April, 1933, with this arrangement of relays. The record from this date until the end of June, 1933, is given in the Table.

Table

Month (1933)	No. of trips	No. of earth faults suppressed by coil
April	Nil	14
May	2	40
June	1	48

During the above period the ammeter recorded 102 faults, all of which were successfully suppressed by the coil, and no inter-

ruption of supply or system disturbance was experienced, except on three occasions when the fault was sustained for a period in excess of the time-relay setting. One of these outages was traced to a broken insulator which allowed a conductor to rest on the cross-arm; another was caused by an unauthorized person climbing a structure and becoming electrocuted; and the third was due to an earth wire falling on one of the phases during a heavy storm. Operating results continued to be excellent, and the possibility of installing such coils for protection of the entire 37·5-kV system was considered.

(1.4) Application of Petersen Coils and Selective Equipment to the Grid Network

The major problem to be solved in this connection was how to effect the isolation of faulty sections of line anywhere on the grid without interrupting the parallel operation of the power stations or using the earth-leakage relays to work in conjunction with short-circuited coils for this purpose. As already explained, line faults caused heavy "kicks" on the power stations and, whilst the coils would reduce the number of outages to a considerable extent, it was considered that a scheme whereby faulty sections could be selected and disconnected automatically without subjecting the power stations to "kicks" would be an ideal arrangement.

Much time was devoted to the consideration of this problem by the late Mr. E. C. B. Walton and the author, who prepared several alternative proposals for consideration of various manufacturers. The scheme ultimately evolved provided for the installation of five additional coils which, with the one already in operation at Sumera; would protect the whole grid network and at the same time permit any section to be made dead without undue disturbance to the set tuning of the coils.

The scheme also provided for the installation of special automatic selectors arranged for operation from the coils or from three single-phase potential transformers with secondaries connected in open delta, the function of the selectors being to control trip-and-close circuits of the oil circuit-breakers in a definite sequence.

Five identical coils were constructed, each having a current range of 19·5 to 9 amp with tappings in 10 steps, a built-in, 20/5 amp current transformer and a winding tap to provide a constant low potential under line-fault conditions for the operation of relays. From experience with the current-operated relay at Sumera it was considered essential to employ potential relays for control of the selectors in order to obtain reliable operation. For this reason, and as a precaution against possible instability of the circuit, the 3-limb type of construction was adopted.

Before deciding upon a definite sequence of isolation the question whether the immediate selection of a particular faulty section could be achieved was considered, and experiments with current transformers in the earth wires at Sumera were made in an endeavour to obtain some reliable indication of the direction of a fault, but the results were not conclusive.

It was therefore not considered practicable to evolve a scheme for the introduction of additional relays to indicate the direction of fault, as it appeared extremely doubtful whether any successful operation of such relays could be obtained.

The capacitance currents of single-circuit and double-circuit sections indicated in Fig. 2 are based on 0·17 amp per mile for single circuit and 0·24 amp for double circuit as a result of experiments performed with the coils.

Two coils were installed at Bahadrabad, two at Bhola and one at Palra. Automatic selectors were located, one each, at Bahadrabad, Roorkee, Bhola, Moradabad and Bhagwara. For the operation of the selectors at Roorkee, Bhagwara and Moradabad, all of which are step-down load points, three single-phase potential transformers were connected to the busbars at each station with the secondaries arranged in open delta.

The general principle of operation is as follows. Assume that a sustained earth fault occurs anywhere on the 37·5-kV system. At the instant of fault the capacitance current is neutralized by the reactive current, which is shared by the Petersen coils, and at the same time a potential difference is produced in the open-delta windings of the potential transformers. The coils and potential-transformer secondaries will remain energized until the fault is removed or isolated.

If the system is divided into two parts by breaking the metallic connection of the lines without discontinuing supply to either portion, then the location of the fault in relation to the two parts may be immediately determined, since the neutral-point voltage on the healthy portion will collapse and current in the coils connected thereto will disappear. The potential-transformer secondaries connected to this portion will also become de-energized.

When a line-to-earth fault occurs the impulse from the potential taps on the coils and from the open-delta potential transformers is utilized for the operation of synchronous motor-driven automatic selectors whose function it is to close contacts in the trip-and-close circuits of the breakers at sectionalizing points.

Each selector comprises a motor-driven drum fitted with fingers, arranged at intervals, which close and open a series of contacts in a set sequence. The complete timing adjustment of the selectors and associated relays is such that contacts for "trip" or "close" of breakers at each end of a section of line are made at the same time by two independent selectors, which enables simultaneous disconnection or re-connection at each end of the section to be effected.

The Roorkee–Saharanpur section is the last in the sequence of operation for the second half, and if a sustained earth fault occurs on this section the selectors will come into operation after an interval of 6 sec, which is the period allowed for temporary faults to clear. The sequence of operation, which is illustrated step by step in Fig. 3, is as follows:—

Operation 1. Breakers No. 4 at Bhola and No. 1 at Moradabad open at the same time. This operation splits the system into two portions shown in Fig. 2 as the upper half and lower half respectively, and does not interfere with the parallel operation of the power stations or the supply of power to the network.

As the upper half is faulty the coil connected to transformer B at Bhola and those at Palra and Sumera become de-energized. A relay operated by this coil at Bhola returns to normal and thus opens the trip connection to No. 3 breaker at this station, which breaker would otherwise open when the selector finger closed contacts in this circuit. No sectionalizing takes place on the lower half, and supply to Moradabad is continued without interruption. The following operations will now take place automatically at intervals of 1 sec (see Appendix).

Operation 2. No. 4 at Bhagwara opens. (Moradabad–Bhagwara section isolated.)

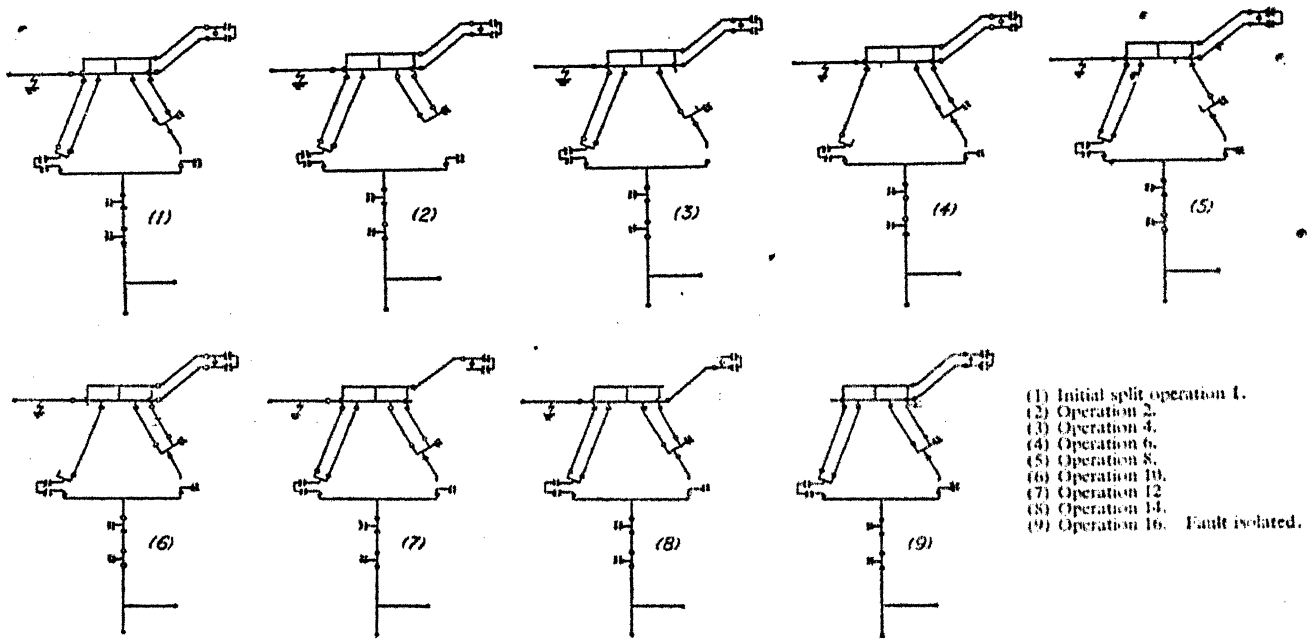
Operation 3. No. 4 at Bhagwara closes. (Supply restored to Moradabad–Bhagwara section.)

Operation 4. No. 1 at Bhagwara and No. 3 at Roorkee open simultaneously. (Ramganga No. 1 circuit isolated.)

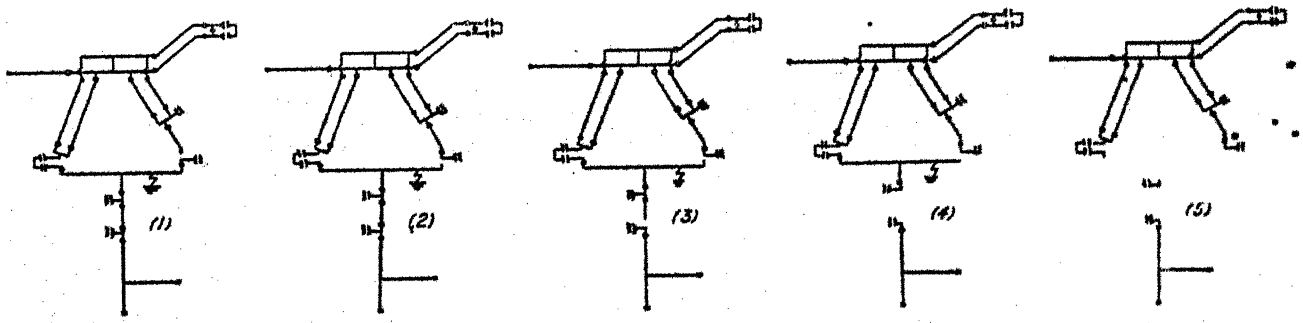
Operation 5. No. 1 at Bhagwara and No. 3 at Roorkee close simultaneously. (Supply restored to Ramganga No. 1 circuit.)

Operation 6. No. 1 at Bhola and No. 5 at Roorkee open simultaneously. (Bhola No. 1 circuit isolated.)

Operation 7. No. 1 at Bhola and No. 5 at Roorkee close simultaneously. (Supply restored to Bhola No. 1 circuit.)



COMPLETE SEQUENCE OF ISOLATION WITH FAULT ON LAST SECTION TO BE ISOLATED ON UPPER HALF



COMPLETE SEQUENCE OF ISOLATION WITH FAULT ON LAST SECTION TO BE ISOLATED ON LOWER HALF
(1) Initial split operation 1. (2) Operations 2 and 3. (3) Operation 4. (4) Operation 5. (5) Operation 6. Fault isolated.

Fig. 3.—Sequence of selection of faulty sections.

Operation 8. No. 2 at Bhagwara and No. 4 at Roorkee open simultaneously. (Ramganga No. 2 circuit isolated.)

Operation 9. No. 2 at Bhagwara and No. 4 at Roorkee close simultaneously. (Supply restored to Ramganga No. 2 circuit.)

Operation 10. No. 2 at Bhola and No. 6 at Roorkee open simultaneously. (Bhola No. 2 circuit isolated.)

Operation 11. No. 2 at Bhola and No. 6 at Roorkee close simultaneously. (Supply restored to Bhola No. 2 circuit.)

Operation 12. No. 1 at Roorkee and No. 1 at Bahradrabad open simultaneously. (Roorkee–Bahradrabad No. 1 circuit isolated.)

Operation 13. No. 1 at Roorkee and No. 1 at Bahadrabad close simultaneously. (Supply restored to Roorkee–Bahadrabad No. 1 circuit.)

Operation 14. No. 2 at Roorkee and No. 2 at Bahadrabad open simultaneously. (Roorkee–Bahadrabad No. 2 circuit isolated.)

Operation 15. No. 2 at Roorkee and No. 2 at Bahadrabad close simultaneously. (Supply restored to Roorkee–Bahadrabad No. 2 circuit.)

Operation 16. No. 7 at Roorkee opens. (Roorkee–Saharanpur line isolated and fault cleared.)

The only breakers which now remain open are those whic opened under Operation 1. These may be reclosed by th operators, and metallic connection of the grid lines restored.

If the fault is on any other section of the upper half, imm diately that section is isolated by breakers opening at each en the neutral-point voltage collapses and the current in the coi disappears. The potential-transformer secondaries also becom de-energized and the whole sequence stops automatically, leavin the faulty section out of service.

The complete sequence of operation for the upper half take place within 20 sec from the initial split at Bhola and Moradabad and the faulty section is located and left isolated within th period.

Furthermore, it will be observed that the power stations con tinue in parallel operation throughout and that at no time does the reduction in capacitance current caused by an isolated sectio exceed more than 15% of the coil tuning, which is within th tolerance under which the coils will continue to suppress the ar successfully.

If after the initial split at Bhola and Moradabad the fau appears on the lower half, coils connected to transformer feeding the upper half and secondaries of the potenti transformers connected thereto become de-energized; thus n

sequence of sectionalizing takes place on this portion of the system.

The complete sequence for a fault on the lower half is as follows:—

Operation 1. Breakers No. 4 at Bhola and No. 1 at Moradabad open at the same time.

Operation 2. No. 1 at Moradabad recloses. (Restores metallic connection of lines at Moradabad.)

Operation 3. No. 2 at Moradabad opens. (Moradabad supplied from upper half.)

Operation 4. No. 1 at Sumera opens. (Link between Palra–Sumera power stations broken.)

Operation 5. No. 2 at Palra opens. (Palra–Sumera section isolated.)

Operation 6. No. 1 at Palra and No. 3 at Bhola open. (Bhola–Moradabad–Palra section isolated.)

As the fault is on the lower half, neutral-point voltage will still exist at Moradabad after the initial split, therefore the selector will continue to operate and is arranged to reclose No. 1 breaker, after which it opens No. 2, leaving Moradabad connected to the upper half.

The time intervals for sectionalizing at Sumera and Palra are controlled by definite-time relays, as the expense of selectors for this purpose was not justified. As soon as the link between Sumera and Palra power stations is broken under Operation 4 it immediately becomes apparent whether the fault exists on the Sumera–Agra–Tundla section or the Palra–Bhola–Moradabad section.

Only when sectionalizing the lower half does it become necessary to interrupt parallel operation between two power stations.

(1.5) Automatic Selectors and Relay Equipment

The special type of selector employed comprises a drum fitted with fingers made from insulating material which when the drum is rotated cause a series of normally open contacts to close for the period during which the fingers are passing over them. These contacts are connected in the trip-and-close operating circuits of the oil circuit-breakers, and the movement of the drum is so slow that the operating currents are broken by the auxiliary switches in the breakers before the selector fingers release pressure on the contacts. The contacts therefore are not required to break but only to make circuits.

The drum is driven through a worm and spur-wheel from a small self-starting synchronous motor so as to ensure the same speed of travel at each station. Between the driving and driven shafts there is a small magnetic clutch which engages the two shafts when energized by the closing of a definite-time relay.

The drum moves against a spring which, as soon as the clutch is de-energized, restores the drum to normal position. Since the fingers will again pass over the trip-and-close contacts as the drum returns to normal, provision is made through the medium of relay D to make these operating circuits dead at the same time as the clutch is de-energized, so that no operation of breakers will occur.

Fig. 4 shows a diagram of an arrangement suitable for use with two coils as at Bhola. The circuit-breaker trip coils are arranged to operate from 24 volts (d.c.) and the close coils from 230 volts (a.c.). From the moment of sustained earth-fault the operation of relays and selector is as follows:—

Immediately neutral-point voltage occurs across the coils, relays A and B, which are of the instantaneous pattern and connected to potential taps on the coil windings, close their contacts.

One set of contacts in these relays, which are arranged in parallel, completes the operating circuit of motor-starting relay D via the closed contacts of relay C. Relay D closes a 3-phase supply to the synchronous motor which immediately runs up to speed.

Definite-time relay E is set in motion at the same time as D, as the operating coils of both these relays are in parallel.

The second set of contacts in relays A and B make the positive connection from the d.c. supply for operating the breaker trip-coils but this circuit remains interrupted by one

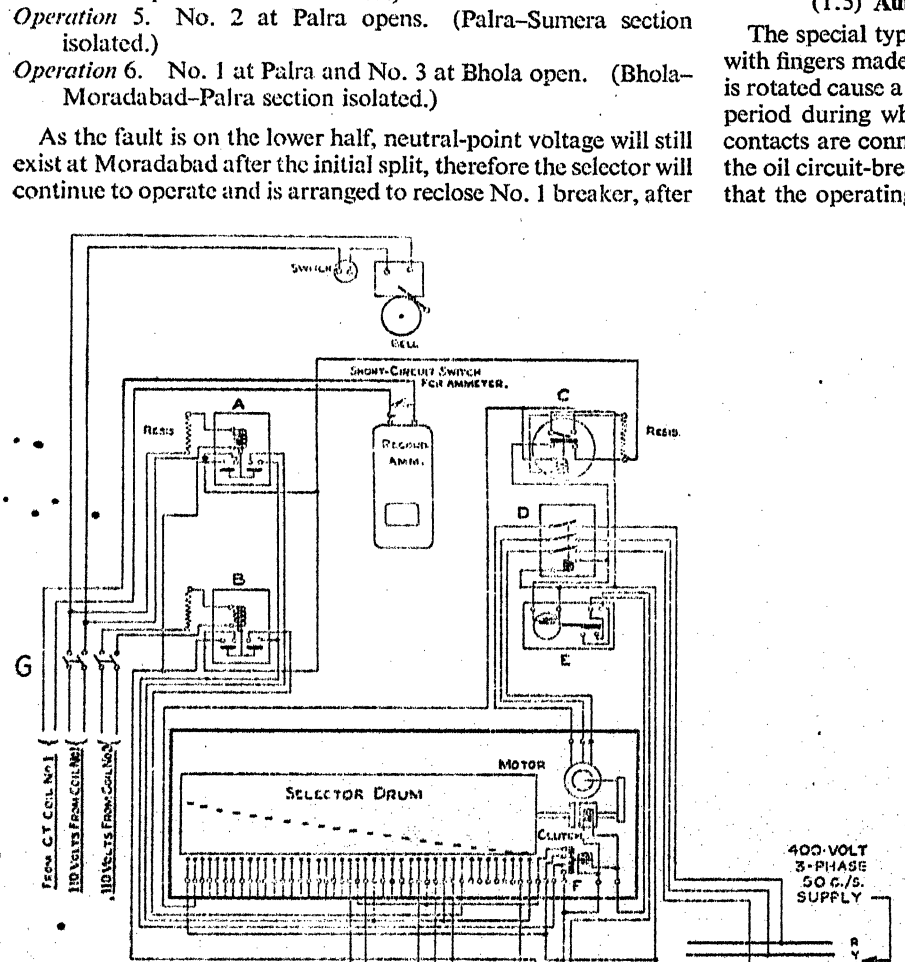


Fig. 4.—Diagram of selector equipment.

Notes:—

All relays shown in reset position.
All breaker-operating circuits shown with breakers closed.
One recording ammeter and alarm bell for one coil only shown.
Immediately No. 4 breaker trips, A or B will become de-energized, depending on whether fault is on upper or lower portion of the grid, and trip circuit to respective breakers will be closed.
G — Disconnecting switches making selector inoperative when required.

set of contacts in relay F and by the selector contacts, which are both in series.

After an interval, relay E closes its contacts and completes the d.c. circuit to the magnetic clutch and operating coil of relay F. The drum is set in motion and relay F further completes the positive connection, the only break in the trip-coil circuit which now remains being across the contacts to be closed by the selector fingers. Relay F also closes one break in the a.c. neutral connection to the breaker-closing coils, thus leaving this circuit to be completed by the selector fingers.

As the drum moves, so breaker trip-and-close coils are energized and movement continues until the breaker controlling the faulty section is opened.

The neutral-point voltage then immediately disappears and relay A or B releases, depending upon which remains energized after No. 4 breaker has opened; thus the clutch and other relays become de-energized and the drum is returned to normal by the controlling spring. Closing of contacts by the selector fingers during backward travel of the drum does not "make" trip-or-close circuits of the breakers, as the d.c. and a.c. supplies are interrupted by relays A or B and F.

Should the fault not be cleared during the complete sequence of operation, as would be the case if a breaker failed to trip or reclose, or if the fault were located inside a substation structure, the drum would continue to move until the last two contacts were made. Closing of these contacts energizes the coil of relay C, whose double set of contacts are make-before-break; thus the relay is held energized through its own contacts. Opening of the lower contacts of this relay breaks the circuit to relays D and E and thus opens the circuit controlling the clutch and relay F. Supply to the motor is interrupted and the drum returns to the normal position. Relays A or B and C remain energized until the fault has been located and the necessary switching operations have been performed.

(1.6) General Information

The number of operations the selectors are required to perform throughout the year is small, as the majority of temporary line-to-earth faults clear themselves within the time allowed. This time may, of course, be increased to any desired figure. To achieve reliability of operation very accurate timing is necessary and periodic checks are exercised. A watch is also kept on the time-constants of the breaker-closing mechanisms. All selectors and relay equipment were set up together and the contacts wired to lamps representing trip-and-close circuits of all the breakers. Time relays and selector fingers, which are adjustable, were carefully set and timings checked with a time-interval meter, after which they were locked. Many hundreds of operations were performed with the indicating lamp-board before the equipments were sent to the respective stations and placed in actual service.

Certain precautions have been taken to guard against interruption of the parallel operation of the power stations or the closing of circuits not already in synchronism in the event of a breaker failing to close owing to some fault in its mechanism. All breakers at the ends of parallel lines are interlocked. For instance, in the normal sequence, No. 1 at Roorkee is arranged to open and close before No. 2 at this station, and, to guard against failure of No. 1 to close before No. 2 opens, the trip circuit of No. 2 is connected through an auxiliary switch on No. 1 so that it is unable to trip unless No. 1 is closed.

If No. 1 fails to close and the fault is on the Roorkee–Bahadrabad No. 2 circuit it cannot be cleared by the selectors, which will continue to the end of the sequence and then lock out. The fact that the selectors remain locked out indicates that the faulty section has not been isolated and that either a breaker has failed to close or the fault exists in a substation structure. Such faults are usually located in a short time, and appropriate switching operations are performed to isolate them.

Arrangements are also provided to make any breaker inoperative for overhaul, or, if a section of line is out of service for maintenance purposes, this is achieved by the insertion of a switch in the trip-and-close connections to the mechanisms. Recording ammeters operated from the built-in current transformers are provided at all points where coils are installed, to record the number of faults. The same purpose is achieved at stations, in which the selectors are operated from open-delta potential transformers, by the provision of recording voltmeters.

It would have been possible to fit electrically-operated mechanisms to the breakers at Hapur and to provide a selector at this station instead of disconnecting the long Bhola–Moradabad–Palra section at one time. This was not done on the grounds of expense and the large extent of de-turning which would take place, as Hapur is only 37 miles from Bhola.

Many additions have been made to the 37·5-kV lines, all of which are protected by Petersen coils. The total number of coils in operation to-day is 12. The "initial split" arrangement has been adopted wherever possible to localize the fault. No further selectors have been provided, and a sequence of operation for these extensions is obtained through definite-time relays.

Operating experience has shown that the capacitance of the lines does not remain constant throughout the year, and during the monsoon months of July–September coil tunings are reduced by 10% to meet the lower capacitance current of the system during this period.

The cost of the five special selectors and associated relays, including installation, amounted to approximately £600. This figure does not include the Petersen coils, or the electrically-operated circuit-breakers which were already in service.

(2) CONCLUSION

The paper has shown that by introducing Petersen coils and automatic selector equipment to the system almost complete immunity from outages due to temporary line-to-earth faults has been achieved, and that in the case of a sustained line-to-earth fault the affected section can be selected and isolated automatically within a period of 30 sec from the instant of fault, without any "kick" being experienced at the power stations.

No pilot wires are required between selector stations. The existing overload relays continue to protect the system against phase-to-phase faults, and if desired the original form of earth-leakage protection may be restored to the system by the manipulation of earthing switches.

Certain criticisms of the scheme are immediately apparent, such as (*a*) the possibility of line surges due to switching operations performed on a system entirely protected by Petefsen coils, and (*b*) the fact that interruption in supply to substations connected to healthy lines between switching points must of necessity sometimes be experienced.

To the former the author can only reply that if surges have occurred their effect has not been observed; the transformers, switchgear and line insulators have not been affected thereby. With regard to the latter, as the majority of faults recorded clear before any sectionalizing takes place and as sustained earth faults are infrequent, momentary interruptions to load points are few. It will be appreciated that the probability of the selectors having to complete full sequence of operation in the event of a sustained earth fault is small, as there are 11 sections on which the fault may have occurred and it is only in the event of the fault being on the last sections in the series, or in a substation structure, that the full sequence of operation takes place.

There is scope for further investigation and experiment in an

endeavour to determine a method whereby accurate indication of the direction of fault may be immediately obtained, and if this can be achieved it is probable that additional relays could be employed to prevent operation of breakers other than those actually controlling a faulty section.

(3) ACKNOWLEDGMENTS

The author wishes to express his thanks to ASEA Electric, Ltd., for their close and valuable co-operation in the evolution of this selective scheme, and to Mr. J. F. Shipley for presenting the paper on his behalf.

(4) APPENDIX

CHART OF TIME SETTINGS OF SELECTORS TO PERFORM SECTIONALIZING OPERATIONS

Operation No.	Operation performed	Roorkee		Bahadrabad		Bhola		Bhagwara		Moradabad	
		Bkr. No.	Time (sec)	Bkr. No.	Time (sec)	Bkr. No.	Time (sec)	Bkr. No.	Time (sec)	Bkr. No.	Time (sec)
	Fault on Upper Portion										
1	Trip	—	—	—	—	4	7·77	—	—	1	7·77
2	Trip	—	—	—	—	—	—	4	10·0	—	—
3	Close	—	—	—	—	—	—	4	11·15	—	—
4	Trip	3	12·23	—	—	—	—	1	12·28	—	—
5	Close	3	13·48	—	—	—	—	1	13·48	—	—
6	Trip	5	14·66	—	—	1	14·66	—	—	—	—
7	Close	5	15·71	—	—	1	15·76	—	—	—	—
8	Trip	4	17·22	—	—	—	—	2	17·20	—	—
9	Close	4	18·38	—	—	—	—	2	18·40	—	—
10	Trip	6	19·62	—	—	2	19·66	—	—	—	—
11	Close	6	20·72	—	—	2	20·76	—	—	—	—
12	Trip	1	21·90	1	21·90	—	—	—	—	—	—
13	Close	1	22·90	1	22·90	—	—	—	—	—	—
14	Trip	2	24·16	2	24·20	—	—	—	—	—	—
15	Close	2	25·16	2	25·20	—	—	—	—	—	—
16	Trip	7	26·6	—	—	—	—	—	—	—	—
	Fault on Lower Portion										
1	Trip	—	—	—	—	4	7·77	—	—	1	7·77
2	Close	—	—	—	—	—	—	—	—	1	8·87
3	Trip	—	—	—	—	—	—	—	—	2	10·10
6	Trip	—	—	—	—	3	13·10	—	—	—	—
						No. 1 at Palra	13·10				

Note.—On the lower portion operations 4 and 5 are not performed by the selectors but by definite-time relays. This also applies to the opening of No. 1 breaker at Palra under operation 6.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 12TH MAY, 1943

Mr. H. Leyburn: These papers are symptomatic of the change which has taken place in recent years in the attitude of the general public to rural distribution. Formerly, an interruption of supply was not considered very serious. Nowadays, however, the continuity of supply demanded from a rural system is nearly as great as that demanded from an urban system, and yet the price must not be excessive.

As regards the main network, there are two methods available for improving continuity. One is the earthing of the neutral through an arc-suppression coil; the other is the use of automatic reclosing circuit-breakers. I think that on rural overhead lines up to and including 33 kV the arc-suppression coil will eventually be generally accepted. At higher voltages, however, it is probable that automatic reclosing circuit-breakers will be largely used, because the breakers used at these voltages are always automatically operated, and the addition of automatic reclosing equipment is therefore economical.

It is generally admitted that arc-suppression coils produce a great improvement in connection with transient earth-faults. The only outstanding question is whether they should be used also to hold sustained earth-faults, or whether these should be cleared automatically. Although I am in favour of the second alternative, I should like to stress the desirability of supply companies collecting all available information so as to enable the question to be settled on the basis of concrete evidence.

Until recently there has been only one method available for clearing sustained faults from a system earthed through an arc-suppression coil, namely that described by Messrs. Steel and Allwood: if the fault persists for more than 5–10 sec the coil is short-circuited, either directly or through a resistor, and the fault is cleared by the automatic protective gear. Mr. Brown describes an alternative method in which the feeders are switched out one at a time until eventually the faulty one is reached, whereupon the apparatus involved resets itself to normal. Such a method is extremely ingenious and interesting, but although it is applicable to some simple networks I doubt whether it would be satisfactory for the more complicated networks common in this country.

In lightning arresters consisting of a non-linear resistance in series with an arc-gap, the object of the resistance is to suppress the power current which flows when the lightning arrester responds. This is necessary when the system is earthed through a resistor or solidly, but when it is earthed through an arc-suppression coil central arc-suppression is already available, and I consider that the non-linear resistance is then unnecessary. Arc-gaps, and particularly high-speed arc-gaps, will do at least as well and possibly better, because they are simpler, more economical, and better able to drain away lightning currents than lightning arresters.

The system of parallel feeders shown in Mr. Howarth's paper is probably suitable where the loads are fairly heavy, but in rural districts the ring main is usually more economical. Apart from this, I have found—and I should like to have the author's comment on this—that parallel-feeder protection is not now as popular as it used to be. One of the main reasons is that, if one

feeder is disconnected owing to a fault, the protection on the other feeder is lost.

I should like to emphasize the importance of statistics of the behaviour of all apparatus installed on supply systems and the desirability of making them available to all interested persons. One important point is the standardization of the basis upon which service reliability is assessed; in this connection I would point out that Mr. Howarth has used one method and Messrs. Steel and Allwood another. I agree with some of the authors that this and similar points should be submitted to a technical body which I suggest should consist of representatives of supply authorities, of manufacturers, of consulting engineers, and of the Electrical Research Association.

Lieut.-Col. K. Edgcumbe: Mr. Howarth recommends that all current transformers should be tested by passing twice rated current through the primary with open secondary. The passing of rated current under these conditions has often been advocated; but this is the first time I have heard of twice rated current being suggested. When Mr. Howarth says that he measures the secondary voltage, he probably has the r.m.s. value in mind, but this bears no relation to the peak, which constitutes the real danger. I assume that his object is to give the secondary a "good doing," but if so it is too haphazard a method. Surely the right procedure would be gradually to increase the primary current until the secondary showed whatever *peak* voltage had been decided upon. If, on the other hand, his idea is to find out whether, under overload, a current transformer will start to saturate before it should, such a test will not give him the required information.

In the testing of current transformers I have always felt that more use might be made of test windings. Some years ago I suggested that the secondaries of current transformers might be wound double and so connected that, by using one half as primary and the other half as secondary, a primary injection test could be easily made. But I gather that test windings are in disfavour, and I should like to know why.

I notice in Fig. 2 of the paper by Messrs. Steel and Allwood that all the power transformers are star-to-star connected. Is not that rather unusual? It is very convenient in this case because there are a number of neutral points to which voltage transformers can be connected, but I had always understood that there were so many other disadvantages that the practice has not usually been followed. With the more usual delta-star connection and no accessible neutral point, it is quite satisfactory to make an artificial neutral point by means of three capacitors, starred together and connected through a sensitive relay, which performs the same functions as the voltage transformer connected between star point and earth as in the authors' scheme. Actually, such a device is considerably cheaper than three voltage transformers, although slightly more expensive than one. It has the advantage, as compared with the latter, that there is no fear of mal-operation due to triple frequencies.

Mr. J. A. Sumner: This symposium is particularly welcome since it gives valuable data showing how faults occur on rural supply systems. It also gives the layouts of various kinds of protective systems, so that we can easily compare them and have a record of such systems in the *Journal*. I propose to confine my remarks largely to the paper by Messrs. Steel and Allwood. I should, however, like to support Mr. Field's view that it is possible to obtain reasonable continuity of supply to the rural consumer without the need for an elaborate protective system.

The chief feature of these papers is that, probably for the first time, The Institution has presented comparable fault and operating data for three supply systems, and I think that the papers are valuable in giving a lead which may result in a much greater extension of the publication of such a correlation of data in respect of supply undertakings.

For some reason, engineers seem to be afraid to let anyone know that they have a fault on their system, whereas it seems to me that they should be only too anxious to send details of those faults to some central body so as to permit of a scientific assessment of faults for the whole country, with subsequent publishing of valuable information on the matter.

I admit at once the difficulty of choosing a unit for the measurement of what may be called the "fault efficiency of a system." Three criteria are suggested in the papers: the criterion of substation-hour outages, Mr. Field's criterion whereby the percentage of each class of fault is ascertained and compared with the percentage of the preceding year, and finally the mile-hour criterion which Mr. Howarth has adopted.

As an example, one may note from the papers that the areas covered by the three undertakings are in the ratio of 1 (Norwich area), 2 (Lancashire area) and 6 (Wessex area). Should one expect the Wessex area to have six times the number of faults that there are on the Norwich system; and, if not, what is the possible relation between size of area and the number of faults, either in total or of a given class? In other words, what is the "standard area"? This is one of the scientific facts which could probably be ascertained if some central body had sufficient data given to it and the scientific method of examination were used.

In collaboration with manufacturers and supply undertakings, I think that both the parties could obtain valuable information which would save many thousands of pounds in designing apparatus and preventing faults.

I can claim to have had some responsibility for introducing this rather novel symposium giving a comparison of data for three supply areas, and it is my earnest hope that the purpose will be achieved of obtaining, in the near future, an extension of this method of comparison of supply-area faults and operation, with a view to a proper and scientific investigation being carried out on a national scale for the benefit of all supply undertakings and of the manufacturers of apparatus used on those undertakings.

Mr. F. J. Lane: It is interesting to note in three of the papers three different methods of applying the Petersen coil. Mr. Field employs the coil without a short-circuiting switch, and is prepared to leave a fault circuit alive for an appreciable time; Messrs. Steel and Allwood short-circuit the coil through a resistor if the fault is maintained for 5 sec; and Mr. Brown ensures the ultimate isolation of the fault by an ingenious switching sequence. I am satisfied that rapid isolation of a faulted circuit is essential, and to this end I prefer the use of the time-delayed short-circuiting switch across the Petersen coil. However small may be the possibility of shock from a fallen line conductor, it is surely in the public interest to make the conductor dead immediately so that it can be removed safely and quickly.

From the economic aspect, protective gear is all too frequently regarded as "an unavoidably necessary adjunct to the more directly useful part of the system"—a grudging acknowledgment of its necessity and very little appreciation of its usefulness. Expenditure on protective gear brings a direct return by permitting a greater measure of interconnection and therefore more efficient utilization of the transmission system. Such expenditure may also represent an economic alternative to a more expensive, less vulnerable transmission system. Messrs. Steel and Allwood have very wisely planned their protective equipment so that it is readily adaptable to expanded system conditions.

Mr. Howarth emphasizes the desirability of laboratory testing, but I consider that the correct procedure should be to make thorough tests at the works. This would ensure that, before the material leaves the works, the manufacturer is fully cognizant of the conditions likely to be experienced at site, and also that the purchaser obtains all relevant performance data. Supply undertakings should not be expected to maintain laboratories equipped

to ascertain data which the manufacturers, as the designers, should already have obtained.

Mr. Howarth assesses protective-gear efficiency on a mile-hours basis and Messrs. Steel and Allwood on a substation-hours basis. Both methods show a pleasing performance, but both are more dependent on the system arrangement than on the behaviour of the protection, and the high figure may easily serve to mask unsatisfactory features of the performance. On the C.E.B. system the efficiency is determined as the number of faults correctly cleared related to the total number of faults, and this has given for the areas figures (mainly between 85% and 95%) which reflect in a very practical manner the effects of improvements in maintenance and design. I am sorry to note that the authors have included information regarding the various types of fault to the exclusion of information dealing with protective-gear behaviour. The fault report form suggested by Messrs. Steel and Allwood should cater for analysis of the correctness of protective-gear behaviour in each case.

Mr. W. E. M. Ayres: It is only a few years since arc-suppression coils were first tried in this country, and the progress has been so great that three of the papers in this symposium are to a considerable extent concerned with them. Where they have been tried they have usually been adopted. Ultimately, as Mr. Leyburn has said, the majority of our system will be protected in this way. Whether these coils should be short-circuited or not depends on what one is aiming at in the system; and continuity of supply is the most important factor.

Mr. Field mentioned that it is important that the residual current through the fault when the circuit is in tune should be kept to a minimum. This current, he says, is chiefly due to leakage on the system, which is another argument in favour of good insulation and maintenance. But I think it is rather a misconception that this residual current is mainly due to leakage on the system or to losses in the arc-suppression coil. That portion seldom exceeds 4% to 4·5% of the current capacity of the coil —6% would be the maximum. The residual current is always much larger than that, and is a combination of three main factors. There is a certain amount of out-of-tune factor. Then there is the loss factor, which is rather small. Thirdly, there is the harmonic component due to the non-linear characteristics of the coil, and that is the overwhelming portion, as proved by oscillograph records.

The system described by Mr. Brown has many limitations in application, but it has the great advantage that it is not dependent so much on the performance of the instrument transformers. On some systems working in this country with several hundred miles of overhead line and directional relays it is possible to ascertain the direction of the fault by telephoning to the different centres. But in the main these systems have been installed where there is a large capacitive current compared with the normal load current of the current transformers. On the other hand, if the residual current is very small compared with the rating of the current transformer, experience has shown that phase-angle shift in the spill current may cause wrong indication. Recent research, however, has made possible good working in this difficult circumstance.

Mr. J. R. Cowie: The very great differences between the areas dealt with in these papers have to some extent been the justification for the methods adopted. Over large spaces in the Wessex area there was nothing approximating to a township and there were not many centres of industry to afford help. It was therefore a difficult area from the point of view of the distribution of electric supply. It seemed to leave no opportunity whatever for the bulk-supply consumer, who often had no time-interval left for his internal protection.

I am interested in the plea of Mr. Lane that the Petersen coil be given a chance to maintain the supply, but I feel that a fault should be removed after a suitable time-delay, because it can be a danger in rural surroundings to both human and animal life.

Messrs. Steel and Allwood took a long and comprehensive view, but found that they had under-estimated the requirements, because it will be seen that they had to reinforce their mains with new 33-kV lines. I think we should be well advised to-day to exercise more courageous foresight when planning our rural distribution systems.

Mr. H. C. Waters: Our experience in East Anglia confirms Mr. Field's statements. An improvement has occurred since lightning arresters were installed, although the arresters themselves were not trouble-free. Since the design of these was modified they have proved reliable and effective.

Regarding arc-suppression coils, no doubt it is as a result of information which I sent him that Mr. Field states that "No case of personal injury has been reported. . . ." A fatality has since occurred. An aeroplane struck an 11-kV line, severing one conductor and the earth wire. A man going to help the airman became entangled with the broken conductor and received a mild shock, which was maintained sufficiently long to cause electrocution. It was known to be a mild shock because people who removed him received slight shocks only. If earth-leakage protection had been used it is doubtful whether the circuit-breaker would have operated, as the accident occurred some distance from the control point.

Our experience of fuses on 33-kV systems has not been pleasant. On occasions when short-circuits have occurred the fuses have blown to pieces. We have therefore replaced them by circuit-breakers when other adjustments were being made to the system, and consequently there are no 33-kV fuses in use in East Anglia to-day.

It is sometimes suggested that the use of automatic reclose circuit-breakers provided with one reclose may be desirable. Under such circumstances when once the breaker had operated it would be necessary to send a man to reset it, whereas, if the fault is transient and the breaker recloses, the supply is automatically maintained. Three or four reclosures have occurred without our knowledge until reported after routine patrol, during which the switch would be rewound. One reclose only would necessitate sending men out more frequently.

Mr. Howarth confirms our experience that laboratory tests of relays and testing in situ is necessary. We have adopted standard test windings as suggested by Col. Edgcumbe; these have proved very satisfactory.

Messrs. Steel and Allwood give us good fatherly advice on designing a protective system, but they describe a complicated arrangement less reliable than a simpler one would prove to be. They have had to introduce a testing system for checking Post Office lines to ensure satisfactory working. Fundamentally it is unsound to have part of one's protective system under the control of an independent body.

Petersen coils serve no useful purpose when the capacitance current to earth does not exceed 2·5 amp. The authors, after experiencing trouble, scrapped their two small coils and installed one coil for the whole system. This method is undesirable, as the coil will need to be re-tuned to give the best results when the system is sectionalized. We have successfully adopted the use of coils in parallel so placed that we can split our systems, leaving any section to operate with the correct measure of protection.

An unusual arrangement for isolating the 33-kV feeders has been adopted when faults occur on the 11-kV system. I think this arrangement is complicated and that it will prove to be more so when additional 33-kV feeders become necessary.

Dr. P. F. Stritzl: Several speakers have already referred to the great differences between the four districts with which these

papers are concerned. These differences are strikingly illustrated by a comparison of the units sold per mile of h.v. line or cable, which, according to published information, are approximately:

50 000 units per mile in the Wessex area,
1 000 000 units per mile in the Lancashire area,
and 150 000 units per mile in the Norwich area.

In each case the operating results may be regarded as highly satisfactory, and yet the means for reaching a common object have been surprisingly different.

Mr. Field stresses the desirability of reducing the number of circuit-breakers. In consequence it is unavoidable that consumers will be cut off when a line section is tripped. This fact is one of the principal reasons for the increasing popularity of Petersen coils.

Referring to Table 7 in the paper by Messrs. Steel and Allwood, the authors rightly attribute the heavy rise in interruptions following upon the installation of the large coil, to the elimination of weak spots. Similar experience was obtained elsewhere, but in analysing all the data available I could not detect any substantial difference between systems operated in either way. Sooner or later the weak spots are brought out, if not as a consequence of sustained Petersen-coil operation then certainly by lightning and other surges.

The question arising is really whether to spend extra money on additional equipment for covering up existing weaknesses, or on their elimination. If the former course is adopted, as it was at Norwich, the expense under the second heading is not avoided, and on balance it would appear that all the advantage is on the side of the operating method recommended by Mr. Field, deriving the full benefit from Petersen-coil operation.

Thus, any special provision for the automatic isolation of a faulty section would appear to be redundant. Messrs. Steel and Allwood state the reason for applying a short-circuiting device in Norwich. Having now eliminated the weaknesses in the system, do they regard this reason as holding good to-day? If they do, it would be of interest to know what evidence they have to show that the short-circuiting device has a beneficial effect on continuity.

With regard to Mr. Brown's paper, is not automatic tripping unnecessary in a system the insulation of which must be maintained at a high level to withstand the heavy lightning surges bound to occur in that area? Perhaps the author could explain why it was considered undesirable to hold a sustained earth fault by means of the coil.

One result of the increased extension of a network is the more frequent occurrence of increased voltage stress on any one point. This has the effect possibly of advancing the date of a weak spot being revealed, and there may be cases of two feeders tripping where only one would be affected with the network split into sections each one protected by its own coil. The point is perhaps not an important one, but where it is possible to subdivide a large network this may prove an advantage.

I am glad to see that on the Wessex system, and in some instances also at Norwich, no fuses are installed for the protection of 11-kV transformers. The fuse protects only against short-circuits, whereas the chief trouble with distribution transformers is overload. The means almost generally adopted to provide against this contingency is the installation of oversize transformers. The supervision of the temperature of pole-mounted transformers is another remedy.

In order to obtain direct proof of the effectiveness of surge arresters, it would be necessary for a considerable number of arresters to be installed simultaneously. Apart from a reduction of direct damage, arresters usually provide a substantial reduction in the number of fuses blown through lightning surges.

On page 4 Mr. Field mentions arcing horns fitted to transformers. Are these horns fitted to all distribution transformers? At what distance is the horn gap set, and have there been any instances of short-circuits due to simultaneous induced surges in all phases?

Messrs. Steel and Allwood state that the length of sections was not sufficient to enable distance relays to be used. It is now possible to produce distance relays capable of dealing with very short sections, and I suggest there will be a great demand in future for a simplified type of distance relay obtainable at a cost that puts it within reach of the rural undertaking.

In conclusion, I endorse the suggestion of Messrs. Steel and Allwood with regard to the setting-up of a technical committee, with the object of studying fault reports for the benefit of the industry as a whole.

Mr. M. Kaufmann: For me the chief interest of the papers lies in the way in which they reveal the methods by which four different authorities, working independently, have tackled and solved the same problem, namely that of maintaining a continuous supply to the consumer. Since the authors all imply that their solutions are working well, it may be concluded that there is scope for individual initiative and ingenuity. That there is a measure of uniformity in the solutions is to be expected, since most rural distributions systems have much in common.

Whilst initiative and ingenuity are to be encouraged, it should be possible to lay down at least the general lines of a solution for all cases. The respective papers accord different degrees of importance to the economics of maintaining a continuous supply, though all are agreed on its paramount necessity. That its achievement must involve expenditure in some form is accepted, and argument is centred only on the form. The papers by Mr. Field, Messrs. Steel and Allwood, and Mr. Brown, advancing the merits of the arc-suppression coil, represent it as the only practicable form; Mr. Howarth's paper, dealing with a somewhat different type of system, describes an instance of orthodox neutral-earthing with discriminative protection. Thus there is a "majority vote" in favour of the arc-suppressor. It is tempting to apply this particular result to the general case, and its premisses should therefore be examined.

The case for the suppressor rests on (*a*) economy, (*b*) difficulties of access to and maintenance of lines, (*c*) presence of tapped lines and (*d*) preponderance of transient faults. In (*a*) there are many hidden factors, such as the need for raising wholesale the insulation level of the system, and for a high standard of maintenance (including that of the consumers' equipment). Factor (*b*) is two-edged; also the very conditions that often deny access, such as snow and storm, are those that render the suppressor ineffective, and only access for repairs can restore supply. When lines are tapped the case is stronger, since economy of switchgear and lines is the overriding factor, and insistence on 100% continuity of supply is inevitably lessened. Condition (*d*) is essential: to make a system suitable to withstand sustained earth faults can prove very costly; phase faults in any event defeat the suppressor.

A very careful assessment of all these factors may, as in Mr. Howarth's case, show that automatic fault isolation with an alternative feed is the better alternative.

Mr. W. Hill: With reference to Mr. Field's paper, I am rather surprised at the high percentage of bird faults. I believe this figure can be reduced to 5%. The high percentage ascribed to unknown causes would also include a number of bird faults, because these are usually the most difficult to trace. My remarks are borne out by Table 4 in Messrs. Steel and Allwood's paper. My impression is that arc-suppression coils are being used to overcome bird trouble, which I suggest could be better dealt with by improved design.

With regard to lightning, Mr. Field leaves out fuses on the

score of economy, and then puts in lightning arresters, although he has an arc-suppression coil which should deal with a large number of his lightning faults. I do not understand the economics of that step. Lightning faults occur in a very erratic manner. An area of 100 square miles may suffer considerably in one year and then be free from lightning trouble for 10–15 years.

No other speaker has mentioned the trouble due to parallels causing induced currents between overhead power lines and telephone circuits. The Petersen coil may overcome this if it can be left permanently in circuit, but I do not think this is possible, and I should like to know the author's experience in this connection. My own opinion is that the automatic reclosing breaker, which we found perfectly satisfactory even on the 33-kV lines, is very suitable for rural distribution. I should like Messrs. Steel and Allwood to give some figures of costs in connection with interlock protection, because that seems an expensive system to adopt in a rural area.

Mr. F. Bent (*communicated*): I strongly support Mr. Field in his contention that elaborate methods of protection are quite out of place on rural systems of transmission and distribution. The most ingenious and costly scheme of protection will not prevent interruptions and damage to lines caused by thunderstorms and high winds, especially in thickly wooded areas where much trouble is experienced due to falling trees and branches. Such elaborate protection would be of doubtful use in the practical operations involved during such occurrences.

It is possible to obtain a reasonably high degree of security of supply by a well-designed flexible system; a simple and robust construction of overhead lines, and the moderate use of simple protective devices comprising overload and earth leakage relays at the main distribution substation centres, automatic reclosing breakers and a reliable type of h.v. fuse. Too much attention has been focussed on ultra-cheap construction of overhead lines and apparatus at the expense of reliability under stress conditions, resulting in high maintenance costs. Many breakdowns could be avoided by using a higher standard of line construction, incorporating a higher rating of pin-type and strain insulators in conjunction with V-type pole-top brackets.

With reference to 11-kV fuse gear, Mr. Field does not appear to have used on his system a simple type of automatic drop-out link fuse which I have employed extensively in my area of supply, and which has been found to be extremely reliable in operation, inexpensive in first cost, and to possess good discrimination characteristics under overload and fault operation; a further advantage being that a blown fuse is easily detected and can be re-wired on site. Mr. Field's objection to the individual protection of pole-type transformers on account of economy would be overcome by the use of this type of fuse, especially as the fuse link also serves as a live-line isolator switch.

The paper by Messrs. Steel and Allwood gives much useful information, based on wide experience, which should prove valuable to all engineers concerned in rural supplies. The interlocked protective system described by them is far too complex and elaborate compared with the results achieved. Although the system is operated by Post Office lines incorporating no less than seven relays at each end of a protected section, exceptional precautions have to be taken involving constant maintenance to ensure that the apparatus will function. The authors' suggestions regarding protective measures to assist in reducing faults are interesting, and I am in support of the recommendation to use only cadmium copper or hard-drawn copper conductors on rural lines, except that on economic grounds galvanized-steel conductors should be employed for short spur lines supplying farms and isolated premises.

In my opinion many h.v. pole-box failures have been primarily due to expansion and contraction of compound due to extreme temperature-changes, resulting in voids, ionization and consequent failure. I am now using a compound which remains semi-plastic at low temperature with encouraging results, the cable entry into the pole-box being first sealed internally by a layer of oil-resisting compound.

I am opposed to the idea of compulsory returns of breakdown records in detail; most faults are due to well-known causes common to all supply undertakings, and no useful purpose is served by imposing upon an efficient administration more "red tape" than is absolutely necessary.

Mr. A. C. Eden (*communicated*): The high percentage of transient faults given by Mr. Field agrees closely with experience in Mid-Cheshire. For this reason it appeared to us that there was a real need for a reclosing switch-fuse, and in August, 1939, we began experimental operation with a device produced by one of our staff. This was a transfer switch which was used in conjunction with a well-known switch-fuse, in which the fuse tube is hinged at the lower end and drops down when the fuse element blows. The energy of the falling tube was used to operate the transfer switch, so connecting in circuit a similar switch-fuse and thus restoring supply. Four single-pole equipments, each providing one reclosure only, were installed in August, 1939, and the results recorded during a period of 2 years are as follows: total operations, 20; automatic reclosures, 13 (65%); persistent faults, 7 (35%). The experimental transfer switches are now being replaced by permanent equipment, which has been developed from the original design during the period since 1941, and is now marketed in this country.

In Table 1 of Mr. Field's paper the percentages of bird faults and failures due to unknown causes both appear to be high. Bird troubles can be very largely eliminated, but this requires study of birds as well as of the overhead-line design.

We have installed between 50 and 60 of the multi-gap resistance (negative temperature coefficient) type of lightning arrester on systems working at 33, 6·6 and 3·3 kV, and it can be said that these have substantially reduced trouble due to lightning.

I should like to mention that there are several well-known types of oil-immersed switch-fuses, suitable for 11 kV, in which the fuses are withdrawn from the oil by the operation of the switch handle, and thus made easily and quickly accessible.

Mr. G. V. Harrap (*communicated*): The suggestion made in Messrs. Steel and Allwood's paper about the value of adopting a standard form of report sheet is a good one. The plea which has been made in this discussion for a continuous statistical survey of faults to be undertaken by some central organization such as the E.R.A., is one which I would wholeheartedly support. Quantitative results of faults are valuable, but qualitative ones are better. I, like many others, have already found this necessary in assessing faults on a city network.* So far as comparative data were available, they were used to produce some measure of efficiency of operation, and I developed the expression "fault frequency factor" to cover faults per square mile per annum.

Any examination of faults, with a view to remedying them, calls for a classification of the faults into types. In Section 3.6 of their paper Messrs. Steel and Allwood comment upon the results obtained by their own undertaking. It would be valuable if they could give results for a rural system similar to those for a city network, which were given in my recent article.†

Would it be possible for Messrs. Steel and Allwood to give an analysis of the operation of the interlock protection on their system? The use of Post Office lines to act as pilots means that overhead lines are used. Will these not fail at the same time as the power overhead lines they are protecting? Snow and ice, wind and rain, lightning and aircraft all affect both sets of lines

* See *Electrical Times*, 1942, 102, p. 788. † *Ibid.*

at the same time. Have the authors any information whereby they could give the number of occasions when the pilots have been available for a fault, i.e. clearance has taken place correctly, compared with the times that the pilots have failed at the same time as the power lines? How does the cost of renting these Post Office lines compare with the provision of (*a*) an overhead pilot and (*b*) an underground pilot, by the undertaking when equated over the life of the apparatus?

Mr. R. T. Lythall (*communicated*): In Section 3.5 of his paper, Mr. Field refers to the withdrawal type of h.v. fuse, to the difficulties of renewal or replacement, and to the impossibility of providing any indication of a fuse having operated. I agree that the latter is a disadvantage, but he must, I imagine, be aware of other types, equally satisfactory in performance, where the fuse tube swings down like an isolator immediately the fuse element has melted. This gives an immediate indication of a blown fuse. Incidentally, a new development enables the swinging-down of the fuse to operate a repeater switch which gives the feature of a single reclosure, a point favoured by the author in other parts of his paper.

Mr. R. B. Rowson (*communicated*): In Mr. Field's paper separate current transformers are recommended for operating the wattmeter-type relays for indicating faulty sections under Petersen-coil operation. Have ring-type current transformers been tried for this purpose, as suggested by Gross,* and, if so, with what success? In view of the difficulty of tracing faults on Petersen-coil-operated systems—as exemplified by Mr. Brown's paper—attention might be directed to the alternative solution described by Ducrot† who also gives the genesis of the Petersen coil invented by Claude in the 1890's.

I do not appreciate the advantage of omitting to fuse individual transformers. If sufficient care is taken it is possible to devise fuse combinations which will discriminate between h.v. and l.v. faults and at the same time operate more quickly than the feeder protection. As is mentioned in the paper, the very high speed of the carbon-tetrachloride fuse is a disadvantage in this connection, as with h.v. fuses of this type unduly high ratings have to be used.

The author's strictures on automatic-reclosing breakers are timely, and it is suggested that breakers of this type for use at the origin of spur lines should be available with a simple form of earth-leakage protection, as most transitory faults are to earth. Efforts have been made to simplify the reclosing mechanism, and in this connection I should like to know whether the author or his colleagues have any operating data of the capacitance-operated reclosing arrangement used on one of the systems in Florida and described in the *Electrical World* some time before the war.

Turning to Mr. Howarth's paper, it is certainly desirable that the next edition of B.S. 81 should include protective current transformers. Much money has been wasted owing to the installation of current transformers which are quite unable to operate the relays under earth-fault conditions. It is suggested that, given the data the purchaser should demand, the performance of the gear is calculable and a primary injection test is hardly needed.

Are the magnetic directional relays which are used on the Lancashire Electric Power Co.'s system of the same type as those described by FitzGerald?‡ Do any of the troubles one is told to expect actually arise from the use of star/star transformers, as shown in Fig. 3?

I should like to ask Messrs. Steel and Allwood what is meant by "a.c. shunt trip coils" in Fig. 3. Where series trip coils are used, are they time-delayed or instantaneous?

The final column of Table 5 gives an unduly optimistic picture of the efficiency of the protective system. Had there been no faults 100% efficiency would have been shown yet the protective apparatus would not have operated once. The Petersen coil and the lightning arresters are the only "preventive" apparatus described, and for these only the criterion proposed seems to be justified.

Mr. D. C. Field (*in reply*): It is generally agreed that continuity of supply in rural areas is becoming of increasing importance, but that when a system covers a wide area with a relatively low population density elaborate protective systems are economically impracticable. For this reason the discussion has largely dwelt on the use of arc-suppression coils and automatic reclosing devices, both of which are recognized as providing a valuable contribution to the solution of the problem.

With regard to arc-suppression coils there is, however, a difference of opinion as to whether it is desirable to short-circuit the coil on a sustained fault and allow the selective protection to operate or to leave the coil in circuit and maintain supply. The only argument advanced by the advocates of the former practice is that it is desirable in the public interest, but it should be pointed out that, as instanced by Mr. Waters, it is probable that the conditions which might render the second alternative dangerous are also those in which it is doubtful whether automatic protection would operate with certainty. A compromise which should reconcile both points of view is to earth the faulty phase at the supply point.

I should perhaps mention that by no means the whole of the Wessex system is protected by arc-suppression coils; this explains certain seeming anomalies to which attention has been drawn, notably by Mr. Hill. As Mr. Leyburn suggests, lightning arresters embodying non-linear resistors are not really required on arc-suppression-coil systems, as the coil effects the necessary current suppression.

I accept Mr. Ayres's comments on the causes of residual current, and no doubt a third-harmonic component does form an appreciable part of the whole. It is hoped to carry out investigations into the particular case referred to in the paper with this point in mind.

Mr. Rowson's query regarding current transformers is probably due to a deficiency in the wording of the paper. My meaning was that the protection transformers would probably be unsuitable, in which case special transformers would be necessary. Ring-type transformers have been used quite satisfactorily.

Several contributors to the discussion refer to the drop-out type of switch-fuse, with or without a repeating device. Whilst I am aware that this type of equipment is obtainable I have had no operating experience of it; but it would appear that it is not adaptable for use with h.r.c. fuses and so is unsuitable for systems where heavy fault currents may be experienced. I am, however, interested in Mr. Eden's remarks on the subject. I cannot agree with Mr. Bent that this type of fuse is an economical alternative to a simple form of isolator for controlling individual transformers; even the latter might, in suitable cases, be omitted.

Mr. Rowson also questions the omission of fuse protection of transformers. In addition to the economic aspect, already referred to, there are operational advantages in favour of group protection which are mentioned in the paper.

I regret that I have no information regarding the capacitance-operated reclosing arrangement used in California and referred to by Mr. Rowson.

In reply to Dr. Stritzl, arcing horns are fitted on all 11-kV distribution transformers; there are two gaps in series, each $1\frac{1}{16}$ in long. Cases have been known, from the evidence of burning on the arcing horns, of simultaneous flash-over on all three phases.

Mr. Hill and Mr. Eden both refer to the number of interruptions caused by birds. These have shown a marked increase

* *Electrician*, 1939, 123, p. 93.
† *Revue Générale de l'Électricité*, 1939, 45, p. 545.
‡ *Journal I.E.E.*, 1924, 62, p. 561.

recently and are probably due to the greatly increased acreage of arable land. Many of the faults are of the phase-to-phase type, against which the arc-suppression coil is no protection. As Mr. Hill suggests, the cure is largely a matter of design, and the horizontal formation recommended in the paper should show better operating results.

I entirely endorse Mr. Bent's plea for a simple and robust type of line construction; whilst I agree that the V-type bracket gives good service, the horizontal cross-arm, which has other advantages should, if soundly designed, prove equally reliable.

More than one contributor discusses the correct basis for assessing the operating efficiency of a system. I regard electricity supply to domestic consumers as a service to the community and for this reason I have used the number of consumer-hours of non-availability as a measure of its inefficiency.

Mr. Lane thinks I am unappreciative of the usefulness of protective equipment; this is not so. The ingenuity of protection engineers has contributed much towards greater reliability of supply on interconnected transmission systems. My paper, however, concerns rural distribution systems, and it was my desire to put restrictive protection in proper perspective. So long as mains and apparatus are liable to breakdown, so long will protective gear be required; but it remains true that it is an adjunct rendered necessary by the unavoidable weaknesses of the directly useful part of the system.

Mr. Lane's remarks on a criterion of efficiency deal with this question from the point of view of restrictive equipment only. This serves to illustrate that lack of a sense of proportion to which I referred in the paper, and to emphasize my contention that protection bears a wider implication and embraces all means of improving continuity of supply to the consumer.

Mr. O. Howarth (*in reply*): The loss of instantaneous discriminating protection on the remaining feeder when one of a pair fitted with parallel-feeder protection is out of service may account for a reduction in the popularity of this type of protection, as suggested by Mr. Leyburn, but if there has been such a reduction I think it more likely to be due to the development of alternative protective schemes.

Col. Edgcumbe seems alarmed at the idea of passing twice rated primary current through a current transformer with the secondary open-circuited. The test gives an indication of the maximum voltage available to operate a relay—not to a high degree of accuracy, but near enough to remove any doubt in most cases. It also indicates the degree of similarity of the individual transformers comprising a group. Granted the test is fairly severe on the inter-turn insulation, I doubt whether it is more severe than the stresses which may be imposed when a surge passes through a protective current transformer installed on a high-voltage transmission system. I have had several experiences of protective current-transformer secondaries failing in service, but none of a failure due to the test we make. Those which failed in service had not been subjected to this test. Twice rated current is usually about equivalent to saturation point, thus giving maximum secondary voltage. It is admittedly a rough-and-ready test, but it can readily be made on site. If test windings are in disfavour I suggest that it is because they take up room and are therefore not in keeping with the urge to make current transformers fit into the minimum space.

Mr. Lane considers that protective-gear tests should be made at the manufacturer's works rather than in the supply undertaker's laboratory. This means that a fairly competent official of the supply undertaking would have to visit the works, which is inconvenient for a normally staffed undertaking. My experience is that alterations to systems result in protective equipment going out of service, the various items being used in new groupings of equipment. It is not practicable to send the equipment to a manufacturer for test, and to send individual relays for recalibration after overhaul; this work is appropriately carried out in the supply undertaking's own laboratory. Mr. Rowson thinks it desirable to include protective current transformers in B.S. 81: no doubt this will be borne in mind when the Specification is revised. The magnetic directional relays are of the same type as those described by FitzGerald. We have not experienced any troubles due to the use of star/delta transformers.

Messrs. R. W. Steel and **A. W. Allwood** (*in reply*): It is impossible to deal adequately and individually with all the points raised in the discussion, or to give all the detailed statistical information asked for, owing to the limited space allotted for the published reply.

The scheme of protection we have described was not planned until many years after a start had been made upon the construction of the network to which it has been applied, and it was largely a network in being which had to be dealt with. The main problem was to reduce the number and importance of the outages occurring on an extensive system on which a considerable amount of switchgear and apparatus had already been installed. This somewhat restricted the choice of methods, as it would have been uneconomic to make wholesale changes to the system. To erect or lay separate pilots would have been exceedingly expensive as the existing pole lines would have required reconstruction, but where new sections of main distributors were laid the undertaking provided its own pilots. Possibly in the future the development of new types of overhead pilot wires and the relaxation of overhead-line regulations may make it practicable to attach pilots to the existing overhead lines. When such an overhead pilot cable can be used the annual charges on it will probably amount to about 75% of the rent of the equivalent Post Office pilots. Underground pilots for the overhead-line sections are never likely to be economic.

Several queries have been raised as to whether a fault should be permitted to remain on an arc-suppression-coil protected system until it has been located. When separate coils were first used on small sections of the network they were not shunted by earth resistors after a fault had persisted for a few seconds, but the practice was changed when a larger coil was applied to the whole 11-kV system. Which method is the better depends on how many hours in a given period the insulation of the system is likely to be over-stressed under fault conditions. If the total number of insulated points is large, and the result of their breakdown may be serious, then faults which do develop should not be held for long periods by the arc-suppression coil but should be cleared as soon as possible. The amount of residual current also has a bearing on the subject; this may be such as to cause considerable heating, with consequent fire risk in certain circumstances. A further factor is that when an arc-suppression coil is allowed to hold a persistent fault for an indefinite period on an interconnected system, a large number of wattmeter-type indicator relays are required to indicate which feeder is faulty, and in many cases pole-top inspection is necessary to locate the fault. This frequently results in a greater outage time than is occasioned when the fault is caused to develop by short-circuiting the arc-suppression coil and is isolated in the normal manner.

The scheme developed by us is considered by some speakers in the discussion to be too complicated. This of course is only a question of degree; in comparison with the type of protection and control schemes which will be applied to distribution networks after the war—with their supervisory control, remote operating and indicating systems—the present scheme will appear to be simplicity itself. No scheme can claim to be perfect, and it is only by using a particular scheme that its imperfections can be discovered and remedied, so enabling a

further advance to be made towards the ideal. The economics of the scheme has also been questioned; while the cost of the extra relays required may be from £150 to £200 a section, it should be related to the total costs of the network in order properly to assess it in terms of cost to consumers. When it is realized that nearly £1 million has been invested in the rural distribution scheme, the cost of protection on the transmission lines and main 11-kV distributors seems trifling.

The reason for the star/star connection of the 33-kV transformers is that we considered that the vector relationship of the new system which was being created should be standard, or should be such that the system could be paralleled with those of neighbouring undertakings. Inquiry from the Electricity Commissioners showed that no standard had been laid down for the vector relationship of 33-kV systems, and comparison with other undertakings revealed that the 11-kV system was 30° out of phase with its neighbours. The opportunity was therefore taken to ensure standardization, and all the undertaking's 11-kV step-up transformers were re-wound from delta/star to star/star with a tertiary winding, in order to permit both the 11-kV and the 33-kV systems to be brought into phase with those of neighbouring undertakings.

Some speakers criticize the inclusion in the paper of matter dealing with types of faults experienced and the methods adopted for preventing faults. We consider these points to be as much part of the protection of the system as the automatic isolation of faults which have occurred. It was not intended to deal with the behaviour of the protective systems themselves, since a report on this aspect of the matter had already been published by the E.R.A.*

The fault-throwing system for ensuring the complete isolation of the 33-kV transformer-feeder combinations has worked exceptionally well. The arrangement does not isolate the 33-kV feeder when faults occur on the 11-kV system, but only in the event of a fault on the 33-kV line itself, on the transformers or on the 11-kV cable connecting the transformers to the 11-kV switchgear. All these come within the protected zone of the transformer-feeder combination. The arrangement is stable for through fault currents feeding into faults on the 11-kV system.

We are pleased to note the general support for our suggestions regarding the proper recording of fault data, the correlation of the information thus obtained and its publication, together with fault statistics. This information should be made available to the manufacturers so that it may be applied not only with a view to improving protective gear, but also in order to eliminate defects in the design of distribution equipment generally.

Mr. K. I. Brown (*in reply*): In reply to Dr. Stritzl, lightning is not a serious problem in the area served by the Ganges Grid. Continuous earth wires are provided on all lines, including the 11-kV and 400-volt distribution lines, more for the protection of human life and to assist in obtaining reasonable fault current for the operation of protective relays, than as a measure of protection against lightning. Lightning arresters of the oxide-film and Thyrite distribution pattern were installed in the larger substations on the 37·5-kV system, and at the feeding ends of the 11-kV distributors during the early stages of construction; these are still in circuit. The installation of arresters on 11-kV rural lines constructed during recent years has been almost entirely dispensed with.

Certain operating difficulties have been experienced with 11-kV lines which pass over sandy tracts in many areas since the resistivity of the soil is high, especially during the hot and dry weather. One or two instances have been recorded of leakage current through a broken conductor lying on the ground being insufficient to blow a 10-amp 11-kV fuse, yet sufficient to cause vitrification of sandy soil which assumes the form of a crude glass barrel around that portion of the conductor on the ground. The conductor thus becomes re-insulated and highly dangerous.

With regard to insulation of the system protected by the coils, the majority of the line insulators are rated for full 44-kV working, and the transformers are all provided with fully-insulated windings. It is considered undesirable to hold sustained earth faults by means of the coils on this system, not only on account of possible danger to human and animal life (since the cause and physical effects of sustained earth faults cannot be immediately determined) but also because it is felt better to locate such faults and set matters right as soon as possible.

Not all sustained faults are visible from the ground, and, in areas where roads and communications are poor and sometimes non-existent, it is expedient to isolate the line when such a fault occurs to enable the line staff to locate its position by sectionalizing and testing. Furthermore a sustained earth fault cannot be held indefinitely without the risk of another phase being subjected to fault during the holding period. This would, of course, constitute a phase-to-phase fault and considerable disturbance to the system might ensue if the second fault happened to occur on a different section of line.

Mr. Kaufmann mentions the need for raising wholesale the insulation level of a system if the application of suppressor coils is to meet with success. Whilst I am somewhat out of touch with home systems owing to my long absence from England, I believe that it is customary to select and install insulators and bushings designed for normal full-phase voltage working and not line-to-earth potential, and also that it is usual for transformers to be manufactured with fully-insulated star windings up to 33 kV at least. It may be that most of the expense visualized by Mr. Kaufmann would relate to the replacement of underground cables already installed for earthed-neutral working.

I thank Messrs. Ayres and Rowson for their references to methods available for ascertaining the direction of fault.

* "Statistical Survey of the Performance of Automatic Protective Systems" (E.R.A. Report F/T94), *Journal I.E.E.*, 1936, 79, p. 541.

THE HIGH-PRESSURE GAS-FILLED CABLE*

By C. J. BEAVER, Member,† and E. L. DAVEY, B.Sc., Associate Member.†

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SUMMARY

The present position of existing types of high-voltage cables is briefly reviewed and the reasons underlying the development of the gas-filled cable are given. After a brief description of the cable, the design is dealt with in detail.

The cable construction and manufacture are described and then the physical behaviour of the cable in service is considered. Details of the accessories associated with the cable system are given and the routine type and research testing of both cable and accessories are discussed.

After dealing with gas-pressure considerations of the cable system in service and installations carried out, a brief survey of the economic aspect of the cable is given.

It is concluded that the cable system has certain special advantages and that since its technical and economic positions are sound it should, in the future, be a factor to be taken into consideration when schemes involving power transmission at voltages of 33 kV and upwards are envisaged.

(1) INTRODUCTION

On insulated cables for underground use, the principal effect of the increase in the designed working voltages of systems has been to necessitate the use of higher electrical stress values to enable manufacturers to produce cables of practicable dimensions. The urge for economy in the existing lower voltage ranges has also tended to the use of higher electrical stresses in cables for these systems.

It is generally accepted that—given proper materials and manufacturing technique—the required stress conditions for cables for the highest working voltages can be permanently supported in a commercial dielectric, such as impregnated paper, provided gaseous ionization can be eliminated under all working conditions of the cable; or, conversely, gaseous ionization is the only obstacle—from the electrical aspect—to the production of a non-deteriorating or ageless dielectric for high-voltage, highly-stressed cable.

From the physical aspect it is a comparatively simple matter to provide, within a metal sheath sealed off substantially at atmospheric pressure, an impregnated-paper dielectric which is initially free from gaseous ionization up to high stresses, but from a knowledge of the coefficients of thermal expansion of the materials involved it can be shown that under the influence of temperature cycles gaseous spaces must exist within the confines of the sheath when the cable is cool.

The minimum amount of these spaces is equal to the difference between the impregnating-oil expansion and that of the lead sheath, and if these spaces form within the active dielectric the physical condition for gaseous ionization at relatively low stresses will exist.

The more perfect the initial impregnation of the dielectric, and hence its freedom from ionizable gaseous spaces initially, the lower will be the gaseous pressure within the spaces that are formed as a result of a temperature cycle and hence the more susceptible they will be to ionization.

It will be seen that the problem of eliminating the sole deteriorating influence in high-voltage, highly-stressed cables is fundamentally a physical one, and—disregarding the compromises involving restriction of the working temperature range, and limitation of the dielectric stress value—the efforts which have been made to solve it have been on a physical basis, and aimed at the compensation or accommodation of the effects produced in working, so as to avoid the formation of gaseous spaces or to control them with the object of suppressing ionization under working conditions.

For example, in the solid type of cable metallic screenings can be applied over the dielectric, reservoirs consisting of oil-saturated, low-density paper can be provided outside these screenings, and the conductors and hence the insulated and screened cores can be made oval in shape so that any void or space, forming due to sheath distension, will tend to be located outside the active dielectric. It should be noted, however, that if the cables are laid on gradients, longitudinal migration of the oil over the whole cable cross-section will occur, resulting in the extension of the low-pressure voids or gas spaces to the active dielectric of the cable at the upper portions of the gradients. It is possible to limit the amount of ionization which can occur in the solid-type cable dielectric, by the use of thin papers; but within the practical limits of the thinnest paper which can be used in conjunction with a viscous solid-type cable oil without creasing and wrinkling of the paper, it is impossible to limit the ionization sufficiently to allow of the employment of values of electric stress desirable from the point of view of economy.

The foregoing represents the practical position to-day of the so-called solid-type high-voltage cable, and the wide recognition of its limitations has led to the development of a number of types of cable for very high voltages, capable of operating at high stresses and loadings, such as the oil-filled cable, the fundamental principle of which is the maintenance of oil under pressure in the cable; the compression cable in which the suppression of low-pressure gaseous spaces is achieved by the external application of gas pressure to the cable sheath; and the Oilostatic cable in which the same object is attained by using oil instead of gas as the pressure medium.

A brief survey of these types will show that they deal with the effects of, rather than the fundamental physical cause which leads to, ionization in the solid-type cable, and that certain degrees of elaboration and practical disadvantage are entailed in some directions.

For example, in the oil-filled system it is necessary to have oil reservoirs situated along the cable route; in the case of the compression cable, reservoirs have to be installed to deal with the compound expansion occurring within sealing ends and terminals; while in the case of the Oilostatic cable, oil-pressure reservoirs have to be provided at the terminations of the cable.

To obviate these disadvantages, a type of cable is clearly desirable in which the compensating arrangements are self-contained within the confines of the lead sheath, i.e. in which expansion due to temperature-rise is accommodated at constant volume, thereby avoiding the necessity for extraneous apparatus as well as any consideration of gradient, and at the same time suppressing ionization to a predesigned extent.

Such prevention of solid dilatation, and the above-mentioned accommodation at constant volume, can obviously be attained

* Transmission Section paper.

† W. T. Glover and Co., Ltd.

only by substituting gas for the free oil or compound in the solid or oil-filled types of cable, while the suppression of ionization depends on the designed conditions of the gas spaces.

As a matter of historical interest, the use of high-pressure gas to suppress ionization in cable dielectrics was first suggested by Fisher and Atkinson in the U.S.A. (U.S. Patent 1524124, granted 1925).

It would appear desirable at this juncture to define the "Gas-filled cable" which is the subject of this paper.

(1.1) Definition

The term "Gas-filled cable" implies a cable in which the dielectric is comprised of pre-impregnated paper, carrying no free compound, and in which all spaces in the dielectric (and within the confines of the lead sheath) are filled with gas under pressure.

The gas is a component part of the composite dielectric, and its density and the dimensions of the spaces it occupies in the dielectric are complementary factors in the design thereof.

This definition distinguishes the "Gas-filled cable" from those forms of cable in which gas under pressure is employed to suppress solid-type insulation through the medium of sheaths or membranes acting as diaphragms, and from other forms in which gas under pressure may be embodied or employed.

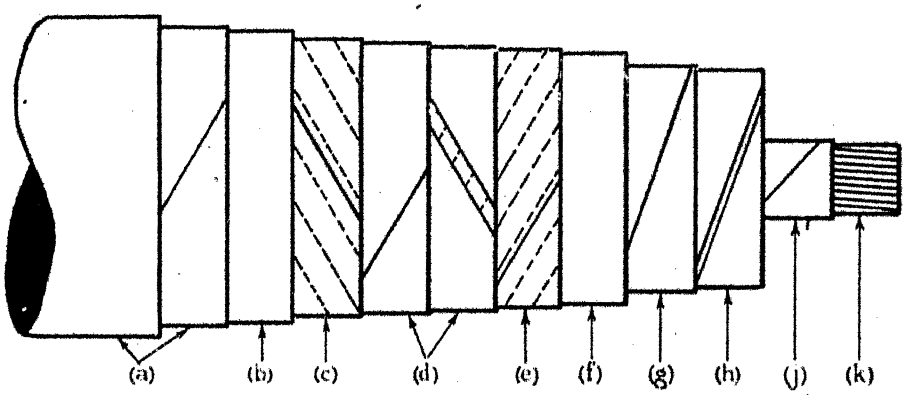


Fig. 1.—Single-core gas-filled cable.

(*a*) Protective covering.
(*b*) 2nd lead sheath.
(*c*) Copper woven fabric tape.
(*d*) Brass tapes.
(*e*) Copper woven fabric tape.
(*f*) 1st lead sheath.
(*g*) Copper tape.
(*h*) Dielectric.
(*j*) Metallized paper.
(*k*) Copper conductor.

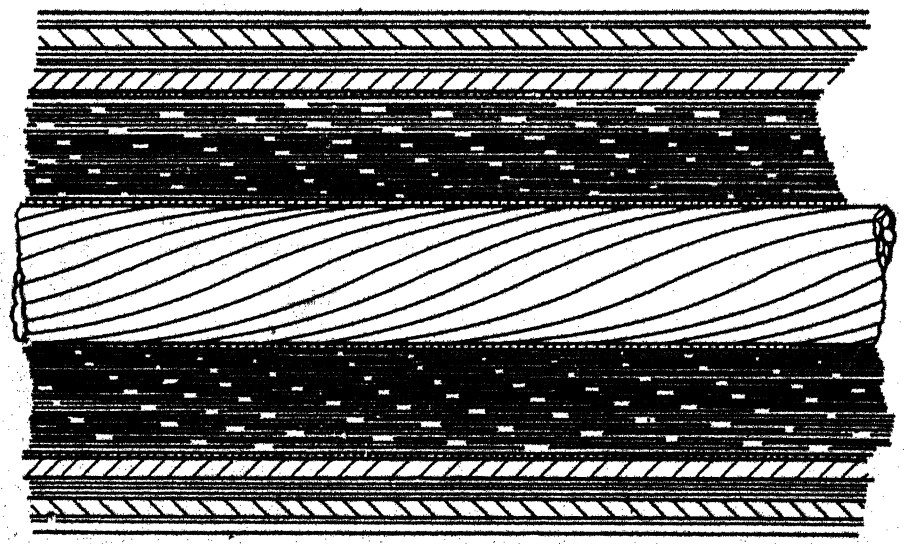


Fig. 2.—Longitudinal section of gas-filled cable.

(2) DESCRIPTION OF THE GAS-FILLED CABLE

The high-pressure gas-filled cable, which is illustrated in Figs. 1 and 2, consists of a stranded conductor screened with metallized papers and insulated with pre-impregnated paper strips, applied to the conductor in air, and having an overall metallic screening. The cable is provided with a pressure-retaining sheath, and this is reinforced mechanically with metallic tapes. A second sheath or further servings are applied over the reinforcing tapes for the purposes of chemical protection.

After the cable has been completely installed, the interior of the pressure-retaining sheath is charged with dry gas up to a pre-designed pressure, and the cable is then sealed off without any auxiliary apparatus such as feed tanks, reservoirs, etc. (British Patent No. 393694).

The gas spaces within the dielectric are provided by the gaps between the edges of adjacent convolutions of the spirally lapped paper strips, and also to a lesser extent between the faces of radially adjacent strips, as shown diagrammatically in Fig. 2.

In the case of multicore cables, the screened cores are laid up and padded to a circular shape by means of drained-type wormings.

(3) DESIGN

(3.1) Performance Basis

(3.1.1) Electrical.

The basis of the design is such that no ionization shall occur, up to 100° C conductor temperature, at a voltage lower than at least twice the designed operating voltage.

(3.1.2) Physical.

The basis of the design on the physical side is that the ratio of gas space to impregnating oil space within the sealed-off sheath has a value such that the gas density at the conductor surface is approximately constant over the whole range of service temperature.

This basis ensures that the pressure variation occurring between the maximum and minimum service temperature conditions imposes a minimum duty on the reinforced sheath.

Another point is that the cable shall be capable of being run vertically for any height or depth without drainage of the impregnating compound.

(3.1.3) Mechanical.

From this aspect the design ensures that no cold working of the pressure-retaining sheath can occur under service conditions.

(3.2) Fundamental Principles

The suppression of ionization within the gas-filled spaces of the cable dielectric is based upon two controlling factors, namely the gas-pressure value and the space thickness. These factors will now be discussed.

(3.2.1) Gas-Pressure Control of Ionization.

One of the fundamental principles upon which the construction of the gas-filled cable is based is that the ionization stress of a gas space existing in insulating material is dependent on the density of the gas within the space. For a given gas at a specified temperature the ionization is thus dependent upon the pressure. The rela-

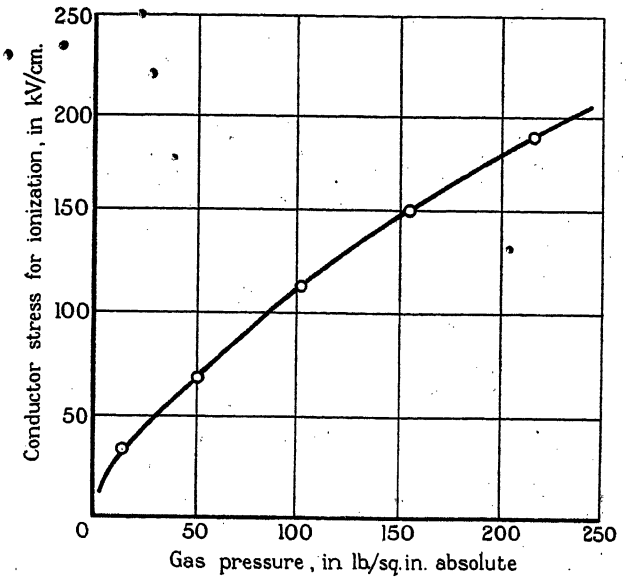


Fig. 3.—Ionization-stress/gas-pressure curve for gas-filled cable dielectric. Tests taken on 0·25-sq in single-core cable with 0·15 in dielectric of 2·5-mil papers charged with nitrogen. All tests at 15° C.

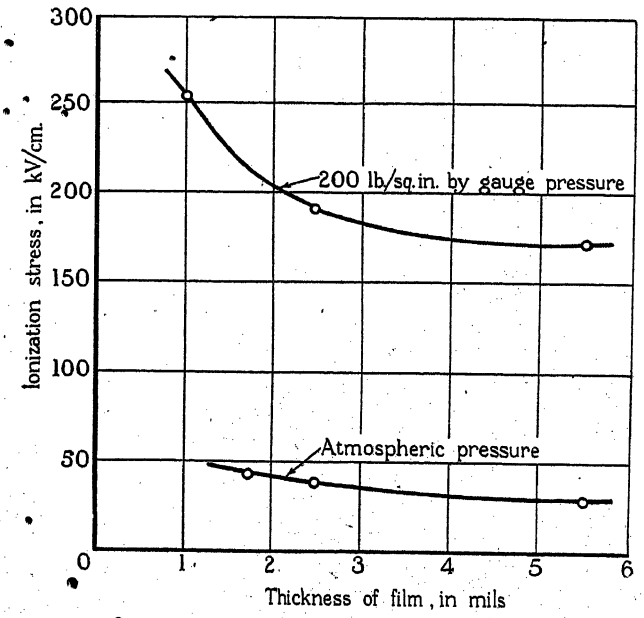


Fig. 4.—Ionization-stress/gas-space-thickness curves for gas-filled cable dielectric. Tests in nitrogen at 15° C. Spaces approximately 0·125 in wide.

tion between the ionization stress of the dielectric and the gas-pressure is illustrated in Fig. 3 for the conditions stated thereon.

(3.2.2) **Gas-Space Thickness Control of Ionization.**

The ionization stress of a gas space existing in the insulating material also varies inversely as a function of the space dimension parallel to the electric field, and Fig. 4 shows this relationship for two values of nitrogen pressure, namely atmospheric pressure and 200 lb/sq in by gauge. It is clearly desirable that the stress in a gas-filled cable dielectric, as well as in any other where gas spaces may exist, shall be radial to ensure that the ionization stress is as high as possible, other conditions being fixed. It should be noted that, if the width of the gas space is comparable with its thickness in the direction of the electric field, the imposed stress within the gas space is lower than for higher ratios,[1] and hence the stress in the dielectric necessary to produce ionization within the space is higher. Generally, however, in cable dielectrics it is necessary for mechanical reasons to have gas spaces between the edges of the paper strips with width/thickness ratios well beyond the value necessary to influence the stressing in the gas space.

(3.3) Discussion of the Factors Involved in Design

(3.3.1) **Gas-Pressure Value and Electric Stressing.**

It is well known that, considering a circular-conductor cable, the radius R of the outer boundary of the dielectric is related to the maximum electric stressing S_c at the conductor surface by the equation:—

$$R = re^{\frac{E}{S_c r}} \quad \ldots\ldots\ldots \quad (1)$$

where r = conductor radius.
E = voltage between conductor and screen.

It is clear, considering the size of the cable only, that for economy S_c should have as high a value as is safely permissible and that this factor has a correspondingly greater influence for higher voltages.

In the case of gas-filled dielectrics the permissible value of S_c depends, with other conditions fixed, directly upon the gas pressure.

The amount of reinforcement to be used on the cable depends upon the gas pressure and also on the diameter of the cable and hence, for very high voltages, the choice of gas pressure reduces itself to an economic problem of the net effect on the cable cost of variation of dielectric thickness versus the variation of reinforcement in relation to gas pressure.

With regard to lower-voltage ranges another factor enters into the considerations, namely the electric stress S_s at the screen over the dielectric. This stress can be related to S_c and the other parameters of the design by the following formulae:—

$$S_s = \frac{E}{R \log_e \frac{R}{r}} \quad \ldots\ldots\ldots \quad (2)$$

From (1) and (2)

$$S_s = \frac{S_c}{e^{\frac{E}{S_c r}}} \quad \ldots\ldots\ldots \quad (3)$$

The variation of S_s with S_c is shown graphically in Fig. 5 for various values of E and r.

Thus for high values of S_c, low voltage-ranges and large conductors, the value of S_s will be high. The conductor sizes are generally fixed by the specified current loading and/or short-circuit considerations, and for a given voltage S_s depends on S_c.

The importance of the value of S_s lies in its relation to the overall dielectric terminations within joints and sealing ends and also to the electrical and physical conditions existing in the cable dielectric under gas-leak conditions.

This latter consideration is dealt with under Section 8.3 of the paper. Regarding the former, it should be noted that the tangential stress existing on the core surface at the point of termination of the screen depends upon the product of S_s and the taper of the stress buffer cone. The higher the value of S_s the finer should be the taper of the cone, and hence the higher the degree of workmanship required from the jointer, especially if the buffer is hand-applied.

From these considerations it is desirable that the maximum

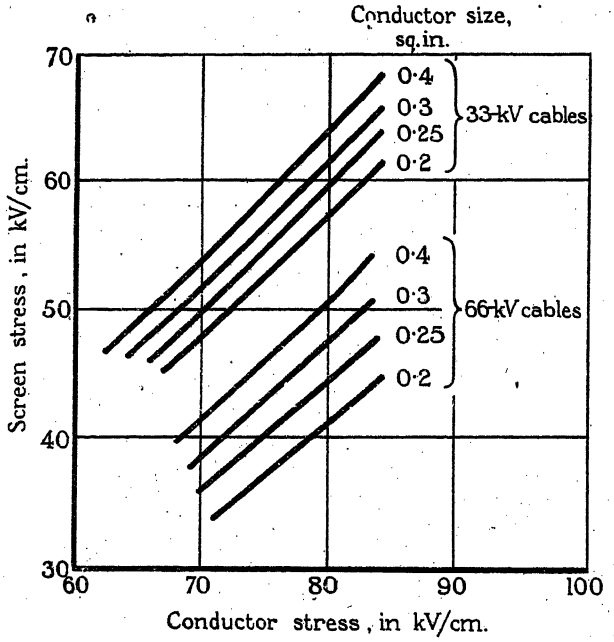


Fig. 5.—Variation of screen stress with stress at conductor surface in circular-conductor cables.

value of S_s should not exceed 50 kV/cm, and this necessitates the use of a value of S_c for 33-kV cables, lower than that required for reasons of economy.

For 132-kV cables a gas pressure of 200 lb/sq in by gauge has been adopted with a corresponding working S_c value of 85 kV/cm, while for 33-kV cables a conductor stress of approximately 65–75 kV/cm has been adopted, corresponding to a screen stress not exceeding 50 kV/cm.

The choice of a stress of 85 kV/cm at 200 lb/sq in gas pressure ensures that no ionization occurs up to at least twice the designed operating voltage (see Fig. 3).

It may be noted in passing that for shaped (oval) cables S_s will have its greatest value at the end of the minor axis, and this will naturally be greater than the corresponding value for a round conductor cable of equal copper cross-section.

In connection with the design of cables for use on unearthed neutral systems or on systems using a Petersen coil, the basis of the design renders it unnecessary to depart from the cable used for systems operating with the neutral point earthed. The suppression of ionization up to twice the working voltage provides an adequate cover for the imposition of full line voltage between conductor and earth.

(3.3.2) **Gas-Space Thickness Control.**

To obtain as high an ionization stress as possible at the conductor surface, it is necessary to use paper of the lowest practicable thickness. The practical limits consist in ability to withstand impregnating machine and lapping machine conditions, and also bending, when incorporated in the cable dielectric, without damage such as creasing, wrinkling or tearing. Damage of such kind would result in loss of control of the gas-space thickness.

It should be noted that the breakage of a paper during the lapping operation and its subsequent replacement by overlapping would result in the formation of a gas space of at least twice the normal thickness. As far as possible, in the inner layers of the paper dielectric, breakages are avoided by the use of spools of papers sufficient in quantity to complete the length of cable which is being insulated.

At greater distances from the conductor, papers graded in thickness in accordance with the distance from the conductor, and hence with the electric stressing, are used.

From the mechanical viewpoint it is desirable to have papers with thicknesses graded in this way, since the movement and mechanical stress on the papers, during bending of the cable, are proportional to the distance from the cable centre. The use of papers so graded results in economy as regards cost of paper, impregnation and lapping processes, without reducing the electric stress rating of the cable.

(3.3.3) **Solid Dielectric.**

The desirable features of the material for the solid dielectric are low permittivity and dielectric loss, low thermal resistivity and high electric strength, as well as satisfactory mechanical properties.

Considering these factors the most satisfactory dielectric is impregnated paper. Dried, unimpregnated paper is unsatisfactory on account of its low electric strength, while its thermal resistivity is higher than that of impregnated paper and its use would also entail moisture-absorption difficulties during jointing.

Dealing with the electric strength aspect, Fig. 6 shows the stress/time curve for a gas-filled impregnated paper dielectric composed of 1·75-mil papers, while the characteristics of a gas-filled dry paper dielectric[2] are also given. The impregnated-paper dielectric has a considerable margin of electric strength over that of the dry paper dielectric, where apparently breakdown occurs very rapidly when the ionization voltage is exceeded. This type of dielectric is, in consequence, weak in its ability to withstand surge voltages.

Other materials such as varnished cambric and varnished silk suffer from the drawbacks of high permittivity and high dielectric loss, and their use for the entire dielectric would necessitate a reduction in the conductor temperature rating to avoid failure by thermal instability. These materials are more costly than pre-impregnated paper, and their only advantage is that they possess superior mechanical properties, the necessity for which has not been found in the gas-filled cable.

Referring again to the impregnated-paper dielectric, it will be shown later that it is desirable, especially for high-voltage cables, to have a certain amount of compound present in the dielectric to provide expansion to compress the gas within the sheath at high conductor temperatures, so that the gas density at the conductor is maintained at all temperatures. This tends to set limits to the specific gravity of the paper. From the electric strength aspect it has been determined that papers having low air-porosities are superior to high air-porosity papers and an example of this is shown in Fig. 6. The specific gravity is related to a certain extent to the air porosity and varies as a direct function of the latter. The values given in Fig. 6 show, however, that a large increase of electric strength can be obtained with a relatively small increase in the specific gravity of the paper and without encroaching on the limits desirable from the oil expansion aspect.

Dealing with the question of the lower limit of thickness for the papers to be used in the most highly stressed dielectric regions near the conductor, the thinnest paper used on commercial cables to date has been $1\frac{3}{4}$ mils; but experimental tables insulated with 1-mil pre-impregnated papers have been successfully manufactured and tested.

It is convenient at this point to mention that examination of the breakdowns in samples similar to those used to obtain Fig. 6, but using a high-impedance test circuit to avoid excessive burning during breakdown, reveals that the breakdowns invariably occur through a butt space and that the fault path is very close (of the order of 0·010 in) to one edge of the paper bounding the space.

The reason for this location of the fault in relation to the width

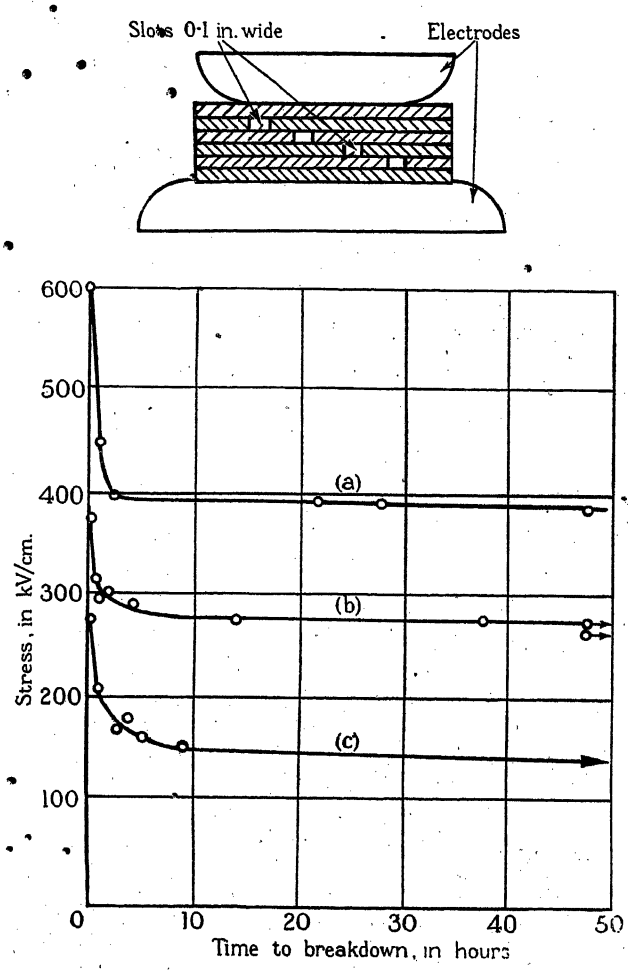


Fig. 6.—Stress/time curves for paper dielectrics under 200 lb/sq in nitrogen pressure. All tests at 15° C.

(*a*) 2·5-mil impregnated paper of low air-porosity value. Specific gravity 0·9. Tested as in diagram.
(*b*) 1·75-mil impregnated paper. Specific gravity 0·8. Tested as in diagram.
(*c*) 1·75-mil unimpregnated paper. Tests on unslotted sheets.

of the butt space may arise from a tendency for the papers on the gap faces to bow or deflect and thus reduce the thickness of the gas space progressively from the side to the centre of the space, while presumably fringing of the dielectric flux will result in a reduction of the stress on the gas space in the immediate neighbourhood of the side of the gap, thus producing an optimum condition for breakdown just beyond this.

An additional point is that if butt spaces exist in the paper next to the electrode, the breakdown invariably passes through one of these in preference to a butt space more remote from the electrodes. Ionization occurs continuously in the gas-filled gaps in these tests, and this consists of a series of discharges occurring between the faces of the gas-filled gaps. These discharges are probably concentrated in channels between focal points on the gap faces, and the intensity of the discharge depends upon the energy feed to the focal points.

Where the butt space is bounded on one face by the electrode the intensity of the discharges on the impregnated paper forming the other face is clearly greater than where both faces are insulating surfaces.

The screenings over the conductor surface are arranged to avoid having butt gaps in the adjacent dielectric bounded by a conducting surface.

Both the above effects have been observed and discussed elsewhere.[3]

The impregnating medium for the paper should have sufficient surface tension to avoid migration from fully impregnated paper having no free impregnant on its surface. For mechanical reasons the impregnant should allow the layers of paper to slide freely during bending of the cable. Highly refined petroleum jellies have been found to give satisfactory results in cables manufactured in this country, but low-loss viscous oils of the type generally used for solid-type cables also give satisfactory tests, provided there is no free compound on the paper surface. In the U.S.A. very high-viscosity oils have been used[3] in conjunction with super-dense papers, and it is claimed that high electric strengths result from their employment.

The permittivity of the gas-filled cable dielectric is 2·8–3·0, and the thermal resistivity 700 thermal ohms per cm cube, at 200 lb/sq in (by gauge) nitrogen pressure.

(3.3.4) **Gaseous Medium.**

The chief factors governing the choice of gas are:—

(*a*) Inertness.
(*b*) High ionization stress.
(*c*) Physical and chemical permanence under all conditions of service.
(*d*) High liquefaction pressure.
(*e*) Low coefficient of solubility in the impregnating oil.

The importance of these factors is fairly self-evident, but the following points may be specially noted.

It is necessary for the gas filling medium to be stable under electrical discharge since, under surge-voltage conditions, ionization or electrical discharge must occur in the gas-filled gaps within the cable dielectric.

Considering the common gases, nitrogen and carbon dioxide, the latter has a high coefficient of solubility in oil, while it is also not as inert as nitrogen. The ionization stresses of both gases are about equal. Other common gases are ruled out under one or other of the factors given above. Up to the present, high-purity nitrogen, i.e. having low oxygen and moisture content, has been standardized for gas-filled cables.

(3.3.5) **Reinforcement Design.**

For single-core cables the metallic reinforcement tapes are composed of brass of quarter-hard temper, while for 3-core cables mild steel is used. In each case a factor of safety of 4 is allowed for the ratio of the ultimate tensile strength of the tapes to the maximum working stress in service. For the purpose of calculating the thickness of tapes a maximum pressure of 250 lb/sq in is taken for the gas pressure within the sheath. Although the reinforcement tapes are applied on the outside of the pressure-retaining lead sheath, the internal diameter of the sheath is taken for the purpose of calculating the pressure load on the reinforcing tapes, and no allowance is made for any residual tensile stress in the lead sheath. These two allowances tend to balance each other.

In any cylindrical pipe subjected to internal pressure the longitudinal stress in the material of the pipe is half the circumferential value. It can be shown that it is possible to apply the reinforcing tapes at an angle θ to the cable axis, such that both the longitudinal and circumferential components of the pressure load are catered for by the reinforcement.

It can be shown that

$$\theta = \arcsin\sqrt{\left(\frac{2D}{2D+d}\right)}$$

where D = outside diameter of the sheath,
d = inside diameter of the sheath.

If the reinforcing tapes are applied with a lay longer than that given by the above angle the reinforced pipe will tend to shorten, while if the lay is shorter the pipe will tend to lengthen. It should be noted that when the strand of the cable is solidly jointed both at joints and sealing ends, i.e. with no expanding connector arrangement, part of the longitudinal pressure load of the cable will be taken by the strand, thus reducing the stress in the reinforcing tapes. Apart from the load imposed on the reinforcing tapes by the gas pressure within the cable, there may be a certain increment of stress due to the differential thermal expansion of the reinforcing tapes relative to the pressure-retaining sheath.

Generally speaking, it is strongly recommended that a second protective lead sheath should be applied over the reinforcing tapes, or, alternatively, an effective form of special protection designed to prevent corrosion of the reinforcing tapes should be applied. If necessary, 3-core cables can be wire-armoured or steel-taped over the second lead sheath for protection against mechanical damage.

Certain 33-kV 3-core cables operating at 100 lb/sq in gas pressure and corresponding stress values have been installed in which the reinforcement consists of single-wire armour, lashed over with short-lay steel tapes and served with protection tapes.

It is felt, however, that standardization in the matter of gas pressure, electric stressing, double lead sheathing, etc., in line with what has been laid down in this Section will be desirable in the future.

(3.3.6) **Cable Types.**

For 33 kV and 66 kV the 3-core screened cable is the cheapest, but 3-core S.L. and also single-core cables can be manufactured. For 132 kV single-core cables have been used up to the present, but it is possible that in future 3-core cables will be practicable, provided that the operating stresses can be considerably increased. This will not present any great technical difficulty, but the choice between the single-core form and the 3-core form will depend upon such factors as the relative lengths of the two types that can be handled, especially during installation, and the total length of the feeder. The latter is concerned because the 3-core cable requires trifurcating joints at the terminations, so that the cable terminations can be made with single-core sealing ends. It is, of course, fundamentally the influence of these factors on the relative costs which will ultimately decide which type of cable is preferable for any particular job.

All the types of cable so far discussed have been the "self-contained" type, i.e. provided with the pressure-retaining sheath; but in the U.S.A. recently an installation of 21 conductor-miles of 120-kV gas-filled cable has been made[3] in which the insulated screened cores, stripped of their lead sheaths, lie in a steel pipe suitably protected to avoid corrosion. The steel pipe line is installed initially and the cables are then drawn in, and subsequently the interior of the steel pipe is charged with gas to the required pressure. The operating results of this system, which was commissioned in December, 1941, will be awaited with interest, especially as they will be directly comparable with those obtainable on a similar length of 132-kV cable of the normal "self-contained" type installed in this country recently.

(4) CONSTRUCTION AND MANUFACTURE

(4.1) Conductor and Screenings

The conductor, immediately after being stranded, is passed through a solid die lubricated with an insulating compound which is subsequently removed from the strand by draining in an oven. The object of this process is to smooth out the surface corrugations due to the circular section of the individual wires, and to provide a flat bed for the application of two or three thin metallized-paper screenings, which serve the purpose of screening the interstitial spaces between the wires in the outer layer of the strand, of presenting a smooth cylindrical surface to the dielectric, and of limiting the maximum radial dimensions of any gas space within the dielectric to that of the thickness of the individual papers in the dielectric. The method of application of the conductor screenings is shown in Fig. 7. Two perforated

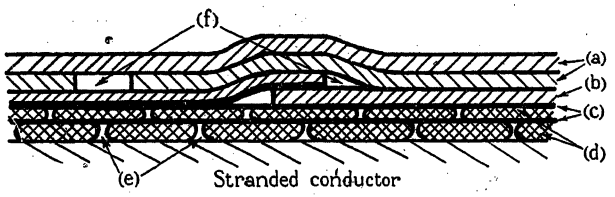


Fig. 7.—Arrangement of screenings over conductor.

(*a*) Insulating papers.
(*b*) Unperforated metallized paper.
(*c*) Metallizations.
(*d*) Perforated metallized paper.
(*e*) Perforations.
(*f*) Gas-filled gaps "A."
Overlap on perforated metallized papers not shown, for clarity.

metallized papers are first applied to the conductor with 10% overlap, and then an unperforated metallized paper is applied with 10% overlap and with the metallized side towards the conductor. The two inner metallized papers are of the perforated type in order that the metallizations shall be connected electrically with the conductor, and the outer metallized paper is reversed in order to ensure that no gap (see "A," Fig. 7) in the dielectric is bounded on the conductor side by a conducting equipotential surface.

(4.2) Dielectric

(4.2.1) **Pre-impregnation of Paper.**

The impregnation of the paper is carried out in roll form in a type of paper-impregnating machine which has been in use for many years in connection with the manufacture of solid-type pre-impregnated paper cables.

The raw paper is unreeled *in vacuo*, passes over electrically heated drying rollers, and then leaves the vacuum drying chamber via a pair of rubber squeegees and enters the compound impregnating tank. After a definite period of immersion in compound the impregnated paper emerges to atmosphere, and while still hot is scraped by two pairs of knives and is then reeled on to a mandrel at the rear of the machine. The scraping is carried out at 95–100° C, and thus there is no free compound on the paper surface up to at least this temperature.

Complete latitude is afforded, by the nature of the impregnating process, in the choice of the characteristics of the impregnating compound to meet the necessary electrical and physical requirements. This type of machine is now superseded by the machine of the type shown in Fig. 8 in which the drying of the paper is carried out in the atmosphere. The paper subsequently passes through the vacuum chamber for the evacuation process and then into the compound tank for impregnation. The main advantage possessed by this machine over the previous type is that much higher temperatures can be used on the drying rollers, and hence greater speeds and greater outputs can be obtained without risk of the paper scorching during a stoppage. The effect of drying the paper in the atmosphere instead of *in vacuo* is practically negligible as the drying temperature is such as would produce a vapour pressure in the moisture of the order of 100 atmospheres, and hence the effect of a back pressure of 1 atmosphere is negligible. Any defects in the raw roll of paper can also be observed by the operative of this machine, whereas in the earlier form these defects could only be seen through a glass window.

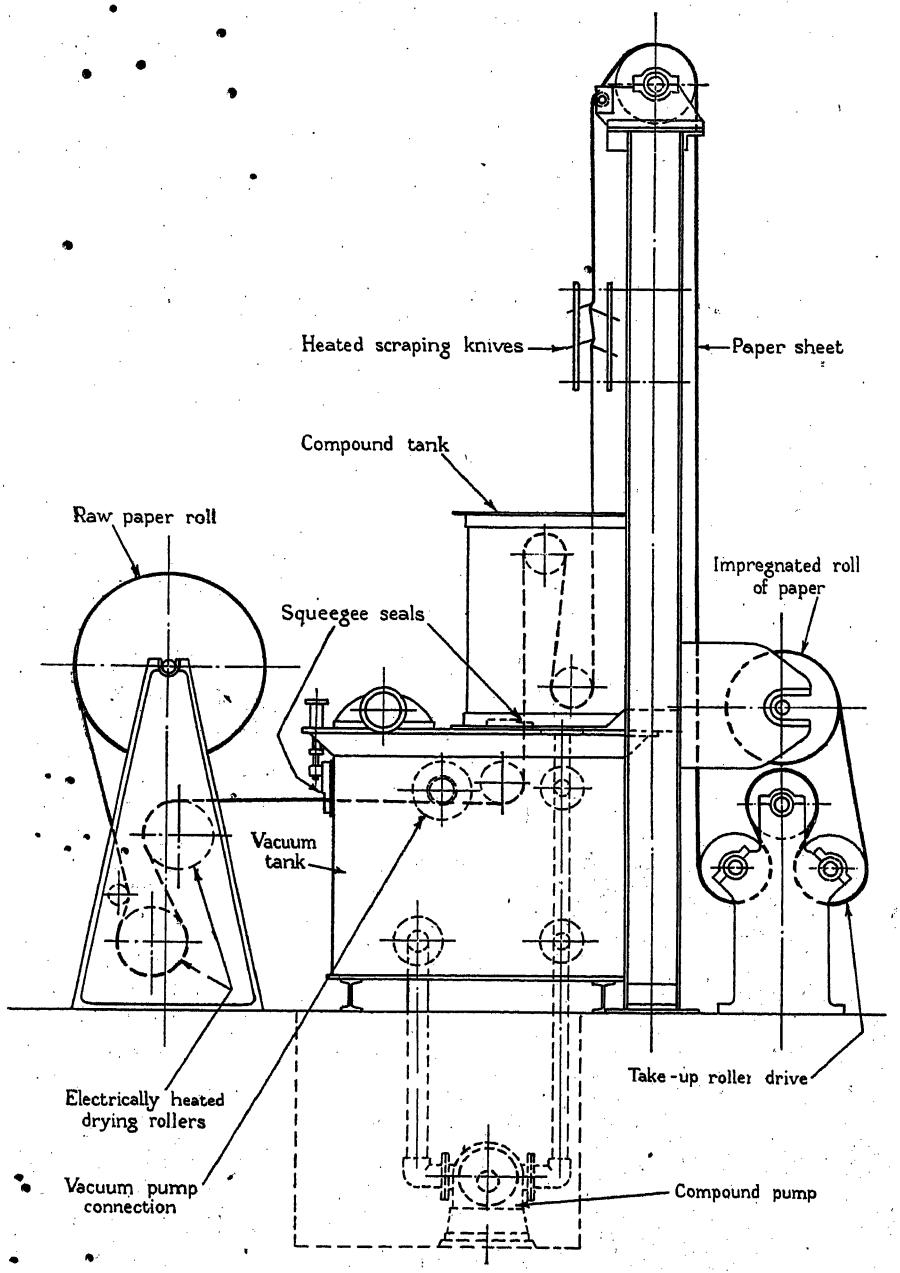


Fig. 8.—Machine for drying and impregnating paper.

The rolls of impregnated paper are stored until required for the lapping operations, when they are cut into spools. The impregnated paper in roll form can if necessary be kept for periods of the order of weeks in the open atmosphere without harmful moisture absorption, but in spool form the maximum safe period of storage in open atmosphere is of the order of days. The dielectric power-factor/temperature curve shown in Fig. 17 is typical of gas-filled cable dielectrics made in this way.

(4.2.2) **Application of Paper Strips.**

The pre-impregnated papers are applied to the conductor, in air with no special control of humidity, with normal manufacturing lays, and with normal gaps between adjacent edges of paper laps, viz. 3–6% of the paper width. The outer boundary of the dielectric is screened with a 3-mil copper tape applied with overlap.

It is desirable, as in other types of high-voltage cables, that radially adjacent papers should break joint, and in order to ensure this the lapping of the highly-stressed inner layers of paper insulation on gas-filled cables has been carried out on a type of lapping machine in which the cable revolves as it passes through, while the heads carrying the paper-strip spools are stationary. The paper strips pass through slots in a sheet-metal framework fixed to the machine, thus ensuring that each strip is applied to the cable at a definite predetermined longitudinal location with respect to the adjacent strips.

The speed of lapping on this machine is approximately 50 r.p.m., and in conjunction with the large distance between the lapping head and the point of application to the paper this ensures that in the event of a paper breakage the process can be stopped before the free end of the paper is buried in the dielectric. A fairly uniform tension is maintained on the paper strips by passing them over a stationary pin placed as close into the spool as possible, so that a frictional component of tension is added by the pin to the paper tension. At large diameters of the spool when the tension tends to be low, the angle of contact of the paper on the pin is large, and hence a large increment of tension is added, while for small diameters of the spool when the tension tends to be high the angle of contact is small and the increment of tension is also small.

It should be appreciated that in this machine the gaps between paper edges and the registration of the strips can be seen continuously by the operative while the machine is revolving. A total of 100 papers can be applied at one operation through the machine.

(4.3) Lead Sheath

This is applied in the case of single-core cables with 20 mils diametral clearance over the dielectric screen, and in the case of multi-core cables it is applied as a fit over the laid-up cable. It is essential that the sheath shall be sound in quality, so that under service conditions no gas leak shall occur. When the cable is first put under gas pressure, a certain amount of initial distension occurs and it is necessary that this be covered adequately by the minimum distension limit of the lead sheath of the cable. A testing specification to cover this aspect of the design is that 1 000 yards of lead pipe, extruded in lengths equivalent to the lengths used in service, shall be tested by means of an internal pressure of 100 lb/sq in until a burst occurs. The distension of the sheath at the burst should not be less than 5%.

(4.4) Reinforcing Tapes

One or more impregnated fabric tapes, which can be copper-wire woven if desired, are applied over the lead sheath to form a bedding for the metal reinforcing tapes.

In the case of single-core cables the reinforcing tapes are generally of brass and consist of a first layer of tape one-half the total reinforcement thickness, comprising two strips in

parallel, double start, applied at such a lay as to give the correct angle of the tapes with the axis of the cable as discussed in Section 3.3.5 and having a gap of $\frac{1}{16}$ in between adjacent strips, followed by two layers of tape each one-quarter of the total reinforcement thickness and each comprising two strips in parallel, double start, with 10% overlap of one strip with respect to the other and applied in the opposite direction to the first layer of tape and at the same angle with the axis of the cable.

In the case of multicore cables the reinforcing tapes are of steel and consist of 4 layers of equal thickness each comprising 2 tapes in parallel applied with a gap between edges, alternate layers of tape reversed and with the same lay as for brass tapes.

Another impregnated fabric tape is applied over the reinforcing tapes, and finally the second lead sheath and protective tapes are applied overall.

(4.5) General

The gas-filled cable can be made, in the absence of dimensional restrictions, in the single-core, 3-core S.L., or 3-core screened form, and in the last-named case the conductors can be oval-shaped if required.

(5) THE PHYSICAL BEHAVIOUR OF THE CABLE UNDER TEMPERATURE CYCLES

(5.1) Dielectric

When the gas-filled cable is heated a rise of pressure occurs within the sheath, and the quantitative value of this rise is determined by the following considerations.

Assuming that the copper conductor and the cellulose portion of the dielectric have negligible thermal expansions, the excess of the thermal expansion of the dielectric impregnating oil over that of the lead sheath results in compression of the gas within the sheath, while the pressure of the gas is also increased in sympathy with its absolute temperature. Under isothermal or known temperature conditions in the cable dielectric, an approximate calculation can be made for the pressure at any temperature.

At any point in the dielectric during a heating period the gas pressure will tend to rise proportionally to the absolute temperature at the point considered, and it will also rise owing to compression of the gas by the impregnating-oil expansion, which is in turn proportional to the temperature rise. Hence with the other factors fixed the gas pressure tends to rise at a rate greater than linear proportionally to the temperature rise at the point. Considering a single-conductor cable, provided with a uniform dielectric as regards oil and gas content, gas pressure-rises corresponding to the radial temperature curve will tend to be generated during a heating period, and in general a gas flow will occur from the conductor towards the lead sheath. It should be noted that the gas flow within the dielectric is a very facile process compared with the oil flow occurring within a fully impregnated dielectric, owing to the low viscosity of the gas compared with that of oils. For instance the viscosity of nitrogen at 200 lb/sq in, and from 0° to 100° C, is approximately 200×10^{-6} absolute c.g.s. units, while at 0° C a thin mineral oil may have a value of 1·0 and at 100° C a value of 0·01 absolute c.g.s. units.

When the conductor is carrying current and a temperature gradient exists in the cable dielectric, for conditions of equilibrium, i.e. when the gas flow has occurred and the gaseous pressure is uniform throughout the cable, the gas density varies inversely as the absolute temperature at any part of the dielectric, and hence the density is lowest at the conductor surface and increases as the sheath is approached.

In comparing the gas density at any point under the high-temperature conditions with that at the basic cold temperature, however, it must be borne in mind that the gas pressure within the cable sheath under the former condition will depend upon the volumetric average temperature rise of the gas spaces within the sheath, and also upon the decrease of gas-space volume as a result of the impregnating oil expansion.

Thus, since ionization generally commences in the insulation adjacent to the conductor, it will be apparent that it is desirable to arrange for the ratio of oil space to gas-space within the cable sheath to be such that under the worst temperature-gradient condition there shall be no appreciable decrease in the absolute value of the gas density at the conductor surface, compared with the basic cold value.

In actual stability tests on a 132-kV 0·2 sq in gas-filled single-core cable, charged with nitrogen at 200 lb/sq in gauge pressure at 15° C, the pressure rose to 245 lb/sq in gauge when the cable was heated to a conductor temperature of 80° C. Thus the ratio of the gas density at the conductor surface under the hot conditions to that at the basic cold conditions can be evaluated on the basis of the ratio of its absolute pressure to the absolute temperature, to

$$\left(\frac{245 + 15}{273 + 80}\right) \Big/ \left(\frac{200 + 15}{273 + 15}\right) = 0{\cdot}99$$

It will be appreciated from the description of the paper-impregnated process given in Section 4.2.1, that no free compound can exist within the cable sheath up to 100° C, and the cable can be operated vertically without fear of drainage. In effect, up to this temperature, each paper strip holds its impregnating compound by capillarity, and any expansion or contraction of the compound results in a corresponding compression or expansion of the gas cushion surrounding the paper strip.

Another important issue, arising from the fact that there is no free compound but only free gas moving within the cable, is that no deterioration of the oil or paper can occur as a result of physical or chemical activity on the part of the copper conductor, overall dielectric screen or lead sheath. This action has been noted in both solid and oil-filled cables.[4]

(5.2) The Reinforced Sheath

When the gas pressure is first applied to the cable, the lead sheath is forced into intimate contact with the fabric tape bedding under the metal-tape reinforcement until the latter is strained sufficiently to produce the stress necessary to withstand the pressure of the gas within the sheath.

The amount of the initial permanent sheath distension which occurs when the gas pressure is first applied to the cable of the order of 1% and represents the sum of the initial slackness of the tapes relative to the lead, and the hardening strain of the former.

When the cable is subjected to a temperature cycle, the excess thermal expansion of the lead sheath over that of the tape produces an extra strain and corresponding stress in the latter during the heating period. The amount of the strain is 9×10^{-6} and the stress within the tapes would be about 120 lb/sq in per deg C rise of temperature for brass, and 17×10^{-6} and 480 lb/sq in per deg C for steel tapes, if the reinforcement were direct on to the sheath. However, the bedding under the reinforcement provides some relief for this differential expansion and, in line with the above values, extra bedding is being used in the case of steel-tape reinforcement.

The rise in the gas pressure within the sheath, due to the heating, also demands, for equilibrium of the sheath, a corresponding rise in the stress in the tapes. If the extra stress produced in the reinforcement as a result of the differential thermal expansion of the lead and the reinforcement is not sufficient for this purpose, the sheath distends very slightly until sufficient extra stress is produced. As a result of this irreversible pro-

cess the datum value of the stress in the reinforcing tapes is raised.

It should be noted that the amount of the distension, if any, is very small since it is the strain corresponding to the difference of two stresses of the same order of magnitude.

In either case, in subsequent temperature cycles, the lead sheath merely expands and contracts with temperature changes, while the reinforcing tapes, in addition to the same action, may also strain in an elastic manner to allow for the differential thermal expansion of the lead and reinforcement and, incidentally, produce equilibrium of the sheath.

It should be noted that the reason for the sound reversible physical behaviour of the reinforced sheath does not lie fundamentally in the design of the latter but rather in the dielectric design.

The compressibility of the gas volume provided within the sheath is sufficient to limit the rise of pressure at constant volume, when the cable is heated to its maximum temperature, to a value which can easily be resisted by the reinforced sheath without cold working of the lead, and without the use of heavy and costly reinforcement.

(6) ACCESSORIES

(6.1) Straight-Through Joints

(6.1.1) **Single-core.**

The general principles of the joint design are illustrated in Fig. 9, which shows a 132-kV single-core straight-through joint.

The screening tape under the sheath is torn off square $\frac{1}{4}$ in beyond the sheath termination, and $\frac{1}{8}$ in beyond the screening-tape termination the stress buffer is built up of silk tape. The outside of the stress buffer is screened with conducting silk tape and finally lapped over with $\frac{1}{8}$in. diameter lead wire in order to cover the edge of the conducting tape.

Lead-alloy gas pipes plumbed into the cable sheaths connect the gas passage of the cable with the filling domes, which are also connected across by means of a gas pipe to preserve the continuity of the gas-flow passage. The brass-alloy sleeve is in halves bolted together with a gasket between the flanges and provided with extra dummy domes to allow for compound expansion.

The sheaths are jointed to the sleeve by means of cast plumbs which also incorporate the brass reinforcing tapes, which are previously tinned. The sleeve is filled with a high-viscosity bituminous compound to a level just below the lip of the filling orifice, and is placed in a concrete protection box.

The maximum electric stress at the ferrule surface or on the conductor adjacent to it is fixed between the limits of 40 and 50 kV per cm. The chamfer on the trim is standardized at a value of 70 mils radial per inch length, and a similar value is adopted for the taper of the built-up stress buffer at the screen termination. This is logical, since, as mentioned in Section 3.3.1, the maximum radial stress at the screen is 50 kV per cm, which is the same as the maximum value at the conductor surface in

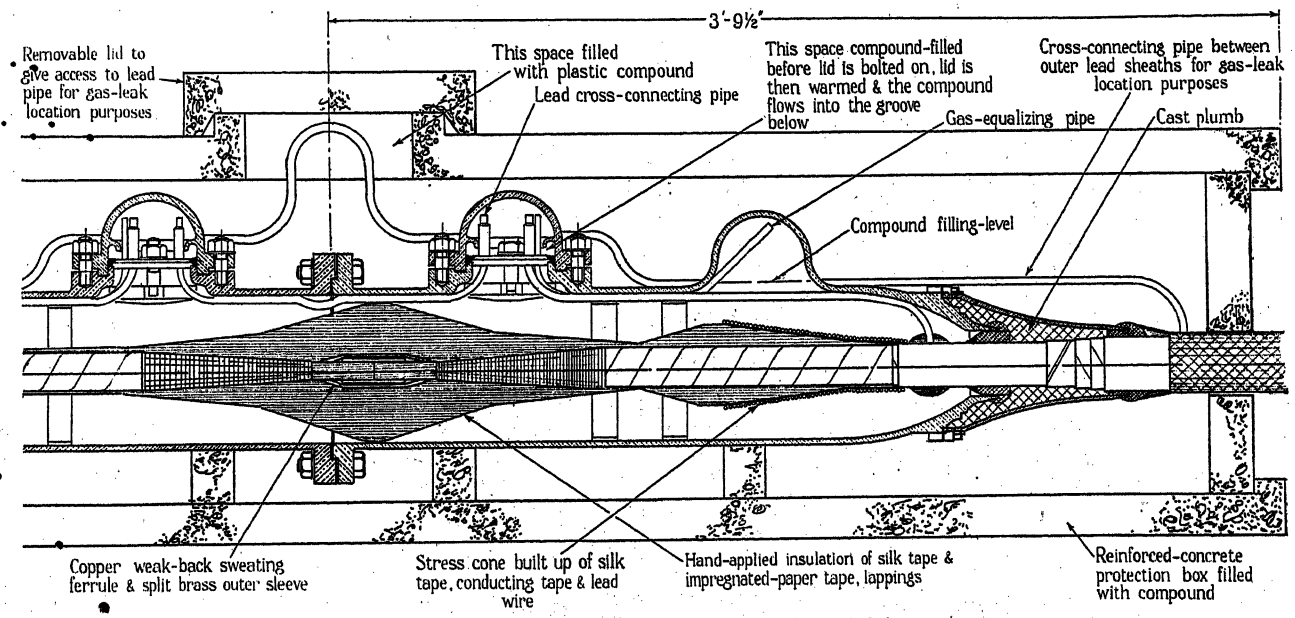


Fig. 9.—132-kV single-core cable straight-through joint.

The conductors are ferrule-jointed and are provided with an outer shell or cover to preserve the continuity of the strand gas passage. The cable trims are chamfered down to the conductor by means of a knife used in conjunction with a chamfering guide. The latter consists of a pair of parallel bars carried on bored ends which can be rotated about the cable axis. The insulation above the bars is cut off by means of the knife until a smooth conical surface is left, and this is finally polished by means of glass paper or cloth.

The ferruled portion of the joint is then insulated, with hand-applied pre-impregnated paper strips interleaved with black-varnished bias-cut silk tape, up to the inner diameter of the joint sleeve. The object of the silk tape is to tighten up the paper tapes and to produce a compact structure.

the joint, and hence the tapers of the trim and built-up buffer should be equal.

(6.1.2) **3-core.**

The principles are the same as for the single-core joint, and Fig. 10 shows a 66-kV 3-core straight-through joint. In this case the stress buffer and the built-up insulation over the ferrule are merged into one composite structure and the conducting tape extends from the screen on one trim to the screen on the other. The cores are separated by means of spacers in order to allow of hand-taping of the cores.

The crotch is filled by means of silk-tape lappings in order to prevent the migration of compound from the joint into the worming spaces. Another point of difference between the 3-core

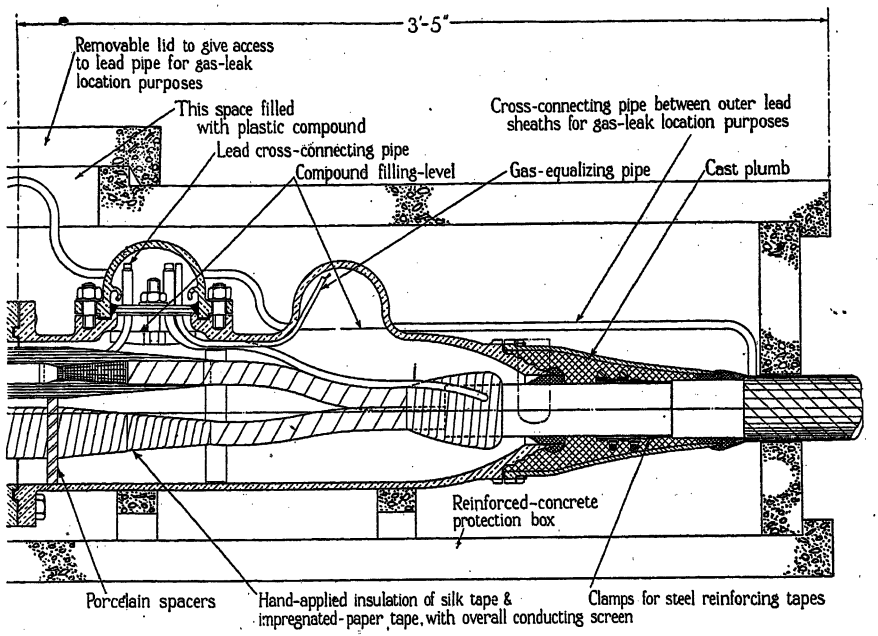


Fig. 10.—66-kV 3-core cable straight-through joint.

and the single-core joints is in the cast plumb boxes where the steel-tape reinforcement terminations are gripped by means of worm-drive clips on to a metal liner passed over the cable sheath and under the tapes. The steel tapes are tinned in order that the plumbing metal will adhere to any exposed portions thereof.

(6.2) Sealing Ends

The general principles of the sealing ends are illustrated in Fig. 11, which represents a 132-kV gas-filled single-core cable sealing end.

The chief feature of interest is the provision of two porcelains, the inner being designed to withstand the internal gas pressure and the outer designed with sheds to give the requisite flash-over voltage.

The stress buffer is built up in a similar manner to that in the straight-through joint and is assisted in the function of controlling the stress by the provision of a metal stress-control cylinder within the base of the outer porcelain. Both porcelains are filled with a high-viscosity bituminous compound. Immediately below the base gland of the sealing end is the brass gas-feed gland which is threaded over the cable sheath and joined thereto at the lower end by means of a cast plumb. The cable sheath within the gas-feed gland is punctured, and gas is fed into the cable via this puncture from a valve and pipe entry into the gas-feed gland. For the lower voltages a single-shedded porcelain is used in place of the two used on the 132-kV sealing end.

(6.3) Trifurcating Joints

(6.3.1) 3-core Gas-filled/Single-core Gas-filled.

A 33-kV joint of this type is shown in Fig. 12, and the only noteworthy feature is the incorporation of 3 single-core cast plumbs within one box at the single core end. Gas-feeding of the system is accomplished by means of a pipe entry into a dome.

(6.3.2) 3-core Gas-filled/Single-core Solid-type Cable.

A 33-kV joint of this type is shown in Fig. 13. The basis of this joint is the provision of a brass barrier plate carrying porcelains with solid copper conductors provided with gaskets under shoulders on the pressure side. The design follows the standard lines except that the bituminous compound is relied upon to insulate the bare ends of the conductors which pass through the porcelain insulators. The gas-feeding of the cable is accomplished in this case by means of a pipe entry into the dome on the pressure side of the joint.

(6.4) Gas-Control Cubicles

The gas-feed pipes from the sealing ends or the trifurcating joints are run to a gas-control cubicle of the type shown in Fig. 14. The gas pipe is terminated with a pressure gauge provided with an alarm contact to operate at a certain minimum pressure, and a small gas valve which is sealed off during normal operation. The gas cylinder is kept in the cubicle together with a gas-pressure regulating valve for feeding gas into the cable system if the necessity arises. Provision can be made for the alarm to cause gas to be fed into the cable automatically.

(7) TESTS

(7.1) Routine Tests.

(7.1.1) Cable.

(7.1.1.1) Gas Test.

After the application of the first lead sheath the cable is charged with nitrogen from one end to a pressure of 30 lb/sq in by gauge and is then sealed off and the pressure recorded. The criterion for gas-tightness is that the pressure-gauge reading, corrected for temperature, shall not fall more than 0·3% (i.e. within the limits of the accuracy of the gauge), during 24 hours. This test is carried out both in the lead-covered and the finished states, the cable being charged from the same end in each case and discharged at the opposite end, so that the air entrained during manufacture is swept out and replaced with nitrogen.

(7.1.1.2) Dielectric Power-Factor/Voltage Test.

This is carried out on the cable in the finished state at atmospheric pressure and temperature. The measurements are made over a range covering the ionization voltage so that the basic power factor and also the ionization voltage can be determined.

(7.1.1.3) Insulation Resistance, Capacitance and Conductor Resistance Tests.

These are carried out exactly as for normal cables.

(7.1.1.4) High-Voltage D.C. Test.

This is carried out on the cable in the finished state at atmospheric pressure and the value used should be 3·5 times the r.m.s. working voltage.

(7.1.2) Accessories.

(7.1.2.1) Gas Tests.

All joint sleeves are subjected to an internal gas-pressure (nitrogen) test of 500 lb/sq in by gauge for 5 minutes while immersed under water, so that any gas leaks can be detected.

The sealing ends are subjected to a hydraulic test of 500 lb/sq in initially, and subsequently to a test of 350 lb/sq in by gauge

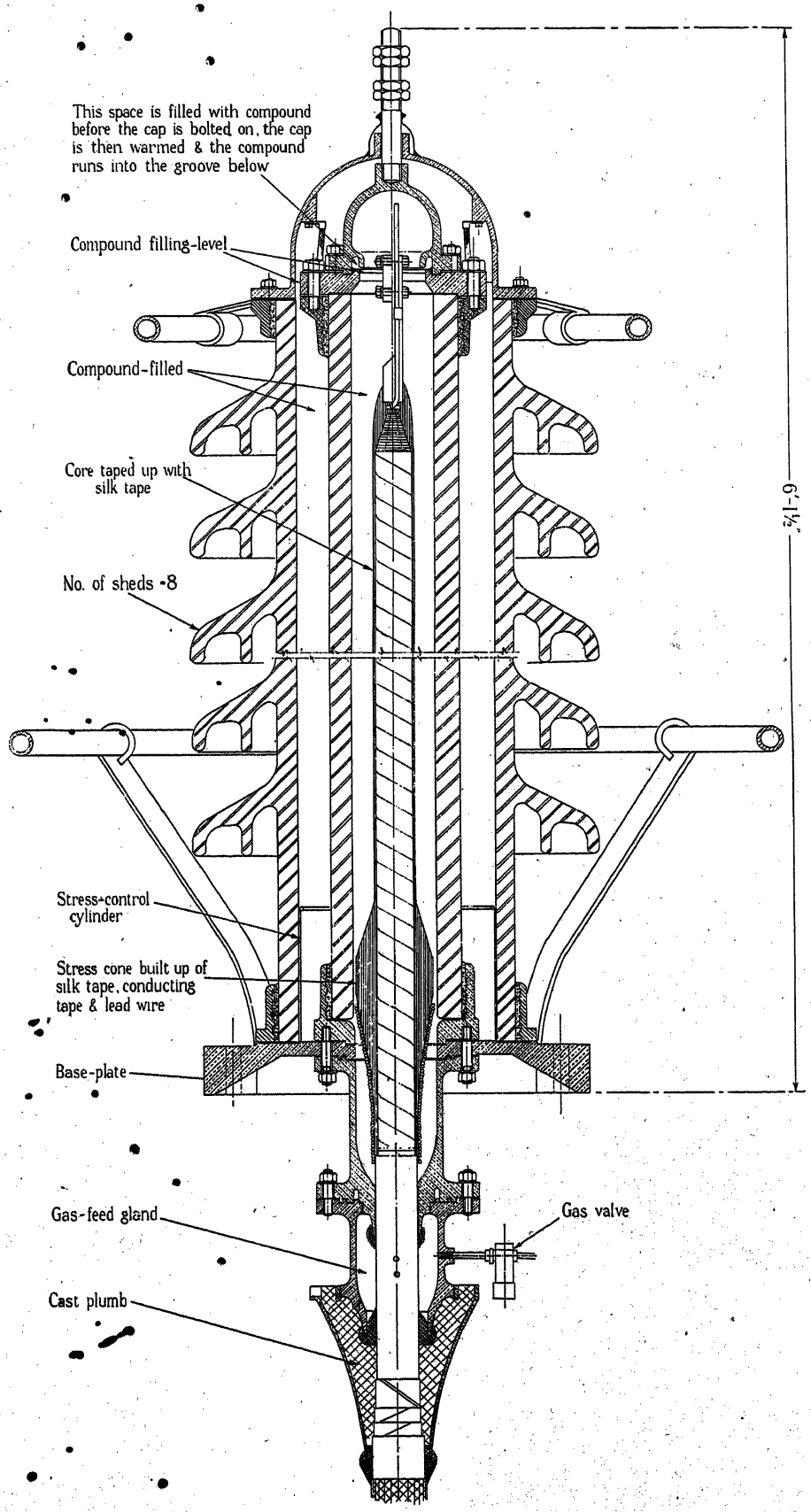


Fig. 11.—132-kV cable-sealing end.

(nitrogen) for 5 minutes. The object of the preliminary hydraulic tests on the sealing ends is to avoid the risk of bursts under gas-pressure conditions. All the above values of gas pressure refer to accessories designed for 200 lb/sq in (by gauge) working pressure.

(7.2) Type Tests

(7.2.1) Dielectric Power-Factor/Voltage, High-Voltage and Bending Tests.

The dielectric power-factor/voltage test up to twice the working voltage is carried out on an unbent sample of the cable under 200 lb/sq in gas pressure, and subsequently the sample is subjected to a high-voltage test of 250 kV (a.c.) between conductor and sheath for 15 minutes for a 132-kV cable.

The standard bending tests specified for normal cables are applied to the gas-filled cable, which after being bent is erected with sealing-end terminations and gas-charged to 200 lb/sq in before being subjected to the voltage test of 175 kV between conductor and sheath for 15 minutes for a 132-kV cable.

(7.2.2) Drainage Test.

All gas-filled cables are subjected to a drainage test as follows:

A length of 1 yard cut from one of these cables shall be suspended vertically in an oven maintained at 80° C continuously for 7 days. Both ends of the cable shall be open, and a lead cup shall be provided beneath the lower end. The maximum amount of compound drainage at the end of this period shall not exceed 1·0% of the internal volume of the sheath.

(7.3) Installation Tests

(7.3.1) Gas-Pressure Test.

After the cable installation has been completed an over-gas pressure test of 250 lb/sq in by gauge (nitrogen) is maintained for 2 days. During this period the gauge readings are recorded and the valves, etc., at the termination are checked for leaks. Subsequently the pressure is reduced to the working value by opening the valve at the end remote from the charging end.

(7.3.2) Electrical Test.

For 132-kV cables a d.c. high-voltage test of 264 kV between conductor and sheath is applied for 15 minutes with the cable at 200 lb/sq in (by gauge) pressure.

(7.4) Stability Tests

(7.4.1) 132-kV Cable Tests.

Figs. 15, 16, 17 and 18 show the test results obtained on a 132-kV 0·2-sq in single-core cable with 0·650 in radial

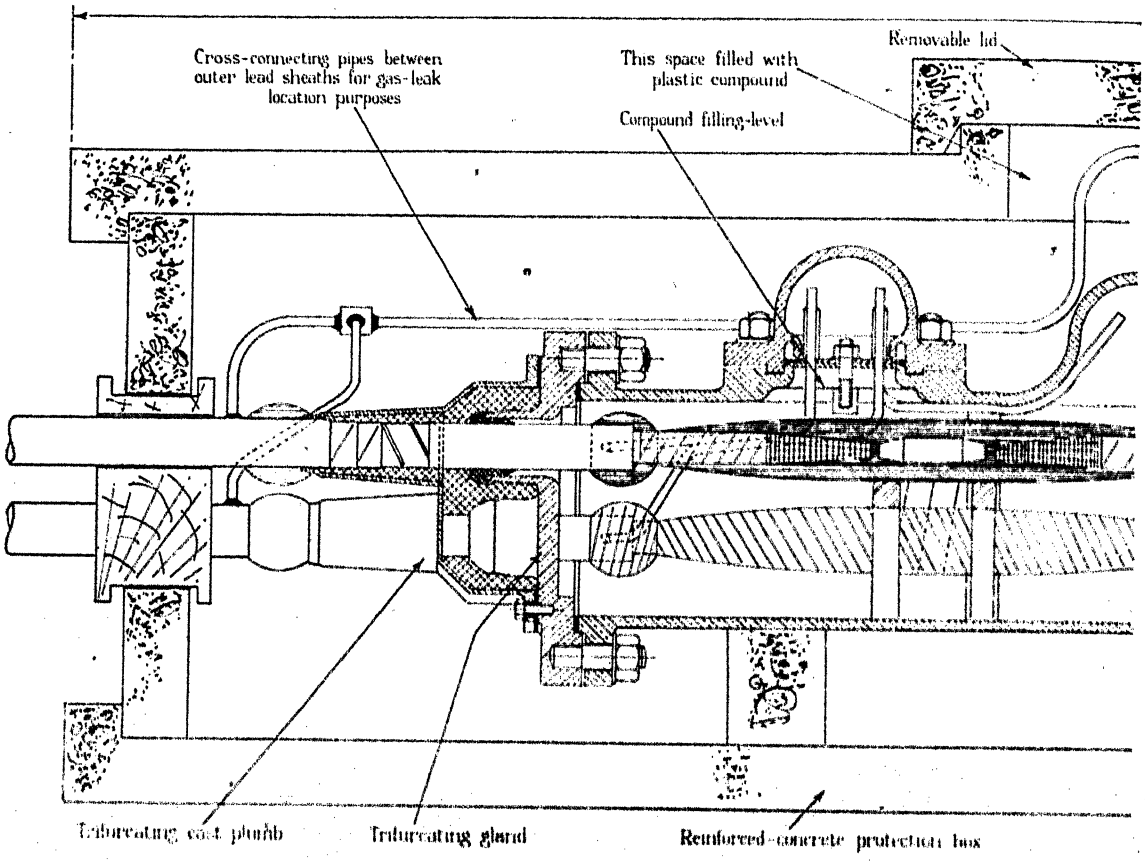


Fig. 12.—33-kV trifurcating joint for 3-core gas-filled cable/single-core gas-filled cables.

dielectric and with a straight-through joint, and two outdoor and two indoor sealing ends included in the run. During the test 1·1 times the working voltage was continuously superimposed on the cable, which was subjected, three times weekly, to 18-hour heating cycles, up to a maximum conductor temperature of 85° C while power-factor/voltage tests were taken up to twice the working voltage, three times weekly, at the cold temperature and occasionally at the hot temperature.

At the end of the test the sealing ends and joints and long sections of the cable, including those vertically-run sections immediately under the sealing ends, were stripped down and examined. No sign whatever of deterioration or ionization was found in any sample.

A further stability test has been carried out on a 132-kV 0·3-sq in single-core cable in which the cable was subjected to approximately sixty 18-hour temperature cycles, up to a conductor temperature of 85° C with 1·33 times working voltage continuously superimposed. During the test, dielectric power-factor/voltage tests were taken up to twice the working voltage at the cold temperature. The installation included two sealing ends situated out-of-doors together with a straight-through joint. During the whole of the test no indication of ionization was detected.

(7.4.2) High-Stress Test.

A length of single-core cable was run at a stress of 140 kV per cm for 42 days with daily temperature cycles to 65° C. Power-factor/voltage tests were taken up to a maximum stress of 140 kV/cm and no sign of ionization was detected. The stress at the screen over the dielectric was 90 kV/cm, and hence the stress buffer controls in the straight-through joint and sealing ends were tested under severe conditions. Samples of the cable joint and sealing ends examined after the test were found to be perfectly free from any trace of ionization effects.

(7.4.3) High Conductor-Temperature Test.

A stability test was carried out on a single-core cable which was heated daily to 100° C while under a maximum stress of 112 kV/cm for 120 days. The power-factor/voltage tests and the subsequent examination of the cable revealed no sign of deterioration.

(7.4.4) High Internal Gas-Pressure Test.

In order to demonstrate the inherent soundness of the physical design of the gas-filled cable system, a length of cable, with a joint included, was run for 9 months without trouble at an internal gas pressure of 350 lb/sq in with daily temperature cycles up to 70° C maximum conductor temperature.

(7.5) Impulse Tests

Impulse tests carried out on gas-filled cables have indicated that the surge strength stress of the cable is 800 kV/cm for a negative 1/50 wave. Development work is proceeding on this aspect of the gas-filled cable. In the U.S.A. certain work[3] has been carried out showing the influence of the air porosity of the paper and of the effect of using high-viscosity oils on the surge strength of the gas-filled cable.

(8) GAS-PRESSURE CONSIDERATIONS

(8.1) Pressure Retention

Pressure records taken on cables during stability tests have indicated that the gas-filled cable system is inherently gas-tight and does not require to be topped-up with gas unless there is a

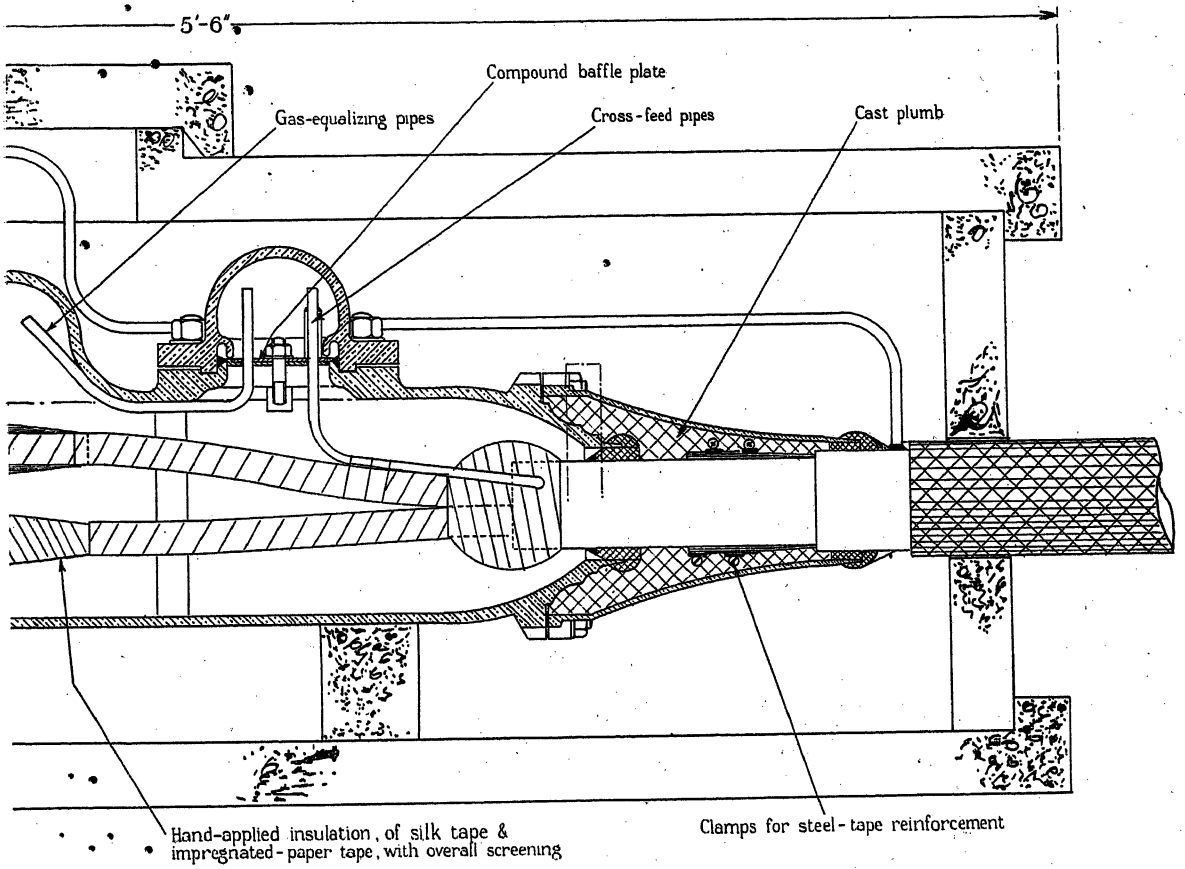


Fig. 12—*continued.*

definite leak on the system. A 1-mile length of 3-phase circuit of 132-kV single-core cable was installed on the C.E.B. system in the latter part of 1937, and it has not been found necessary during the 5 years' period for this installation to be topped-up in any of the phases as regards gas pressure. These tests, and the experience on the other installations listed later in this paper, demonstrate the inherent gas-tightness of the system. By the kind co-operation of users, monthly records of gas pressure on feeders comprised in many of these installations furnish continuous corroborative evidence.

(8.2) Safety Devices

Gauges are installed in cubicles at each end of the feeder and there are minimum-pressure alarm contacts on these gauges which operate audible and/or visual alarms when the pressure reaches a predetermined minimum value. If necessary, it can

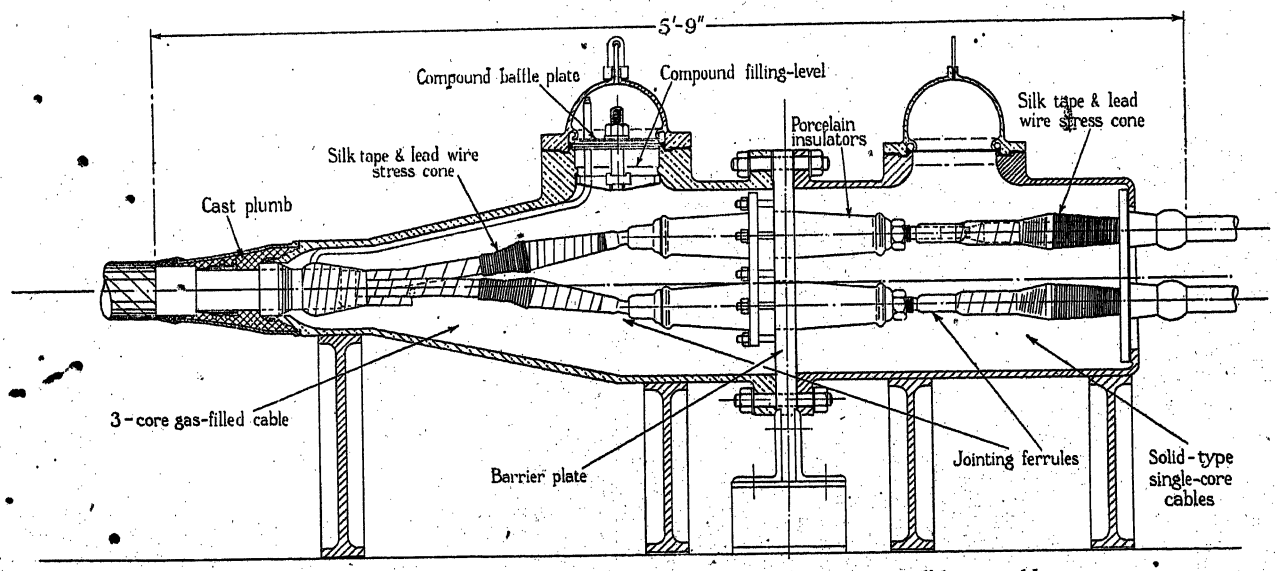


Fig. 13.—33-kV trifurcating joint for 3-core gas-filled cable/single-core solid type cables.

also be arranged for these alarms to operate the pressure-regulating valve on the gas cylinder kept within the cubicle as a stand-by in case of a fall of pressure. In all instances a cylinder of gas complete with gas-regulating valve for feeding in gas at a pressure slightly above the minimum alarm pressure is installed in each cubicle. The minimum alarm pressure for a 132-kV system operating at 200 lb/sq in (by gauge) pressure referred to 15° C is 180 lb/sq in.

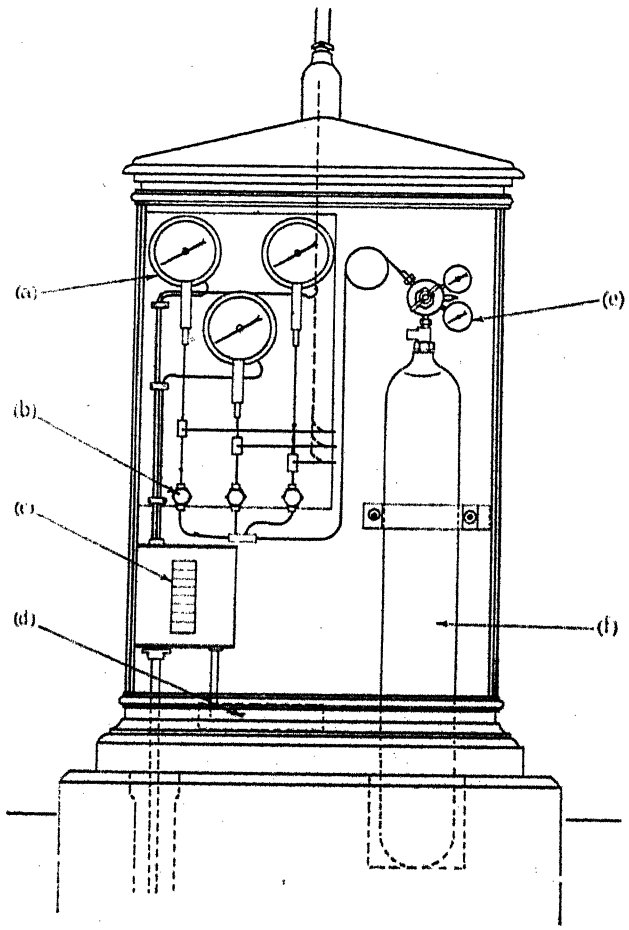


Fig. 14.—Gas-control cubicle.

(*a*) Pressure gauges with alarm contacts to "make" on falling pressure.
(*b*) Stop valves.
(*c*) Terminal panel.
(*d*) Tubular heater.
(*e*) Gas-pressure regulator.
(*f*) Nitrogen cylinder.

(8.3) Cable Under Gas-Leak Conditions

If, due to any cause, accidental or otherwise, a gas leak occurs on a gas-filled cable in service, the question arises as to the possibility of maintaining the cable in service during the existence of the gas leak, and the effects thereof.

If a hollow uniform gas main, in which a leak exists, be fed at each end with gas at a constant pressure, the gas pressure at any point along the main, in terms of the feed pressure, exhaust pressure at the leak, and the leak of the main, is given by the following formula:—

$$P = \sqrt{\left[\frac{(P_1^2 - P_e^2)}{x_1} x + P_e^2\right]} \quad . \quad . \quad . \quad . \quad (4)$$

where P = absolute pressure at the point.
P_1 = absolute feed pressure.
P_e = absolute exhaust pressure at the leak.
x = distance of the point from the leak.
x_1 = distance between the feed point and the leak.

In a leaking gas-filled cable the gas flow between the feed and the leak is mainly along the annulus between the lead sheath and the screen over the dielectric, and since the gas-flow resistance between the annulus and the strand is uniformly distributed along the whole length (uniform lapping and paper spacings) the pressure in the strand eventually stabilizes at a certain mean value of the annulus pressure. This strand pressure can be shown to be approximately 70% of the feed pressure, both being in absolute terms.

In order to determine the practical values of pressure existing in a punctured gas-filled cable the following direct experiment was carried out:—

A length of 0·2 sq in single-core gas-filled cable, insulated with 0·150 in radial dielectric, was terminated in a sealing end at one end, and then gas at a constant pressure was fed in via a gas-feed gland. The other end was also sealed off and pressure gauges

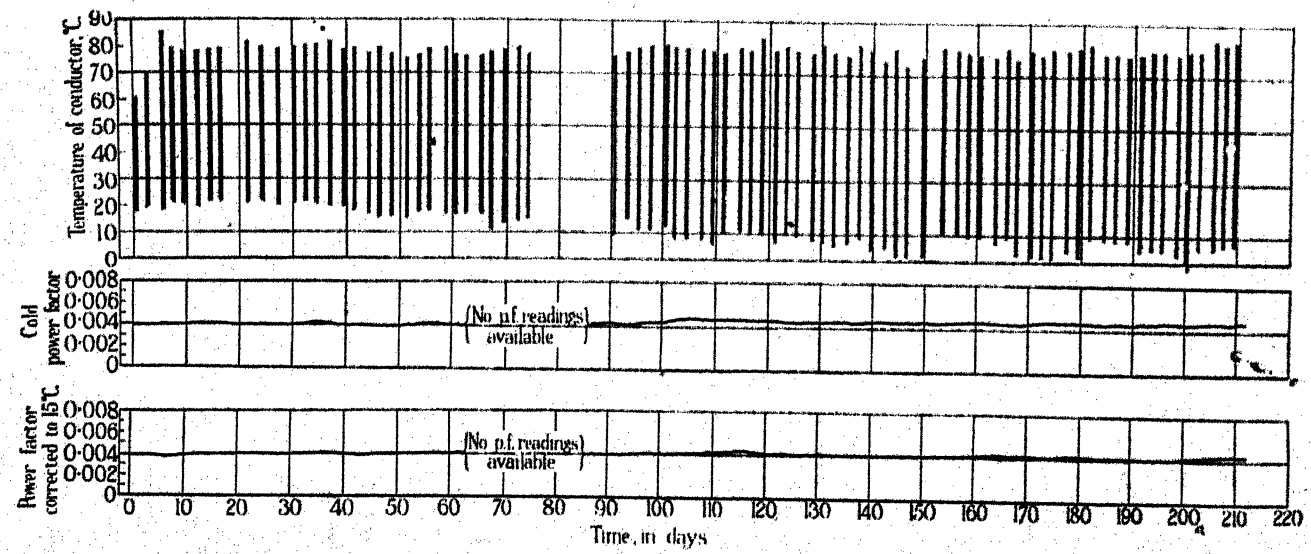


Fig. 15.—132-kV cable stability test, temperature cycle records. Test details as for Fig. 17.

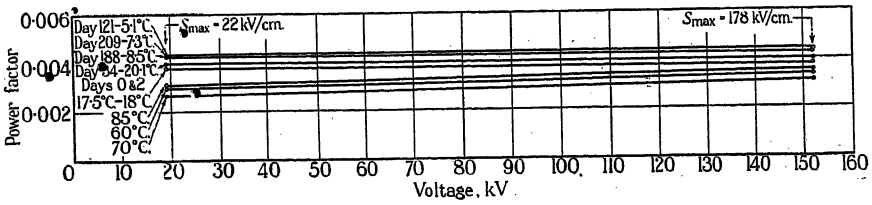


Fig. 16.—132-kV cable stability test, dielectric power-factor/voltage curves. Test details as for Fig. 17.

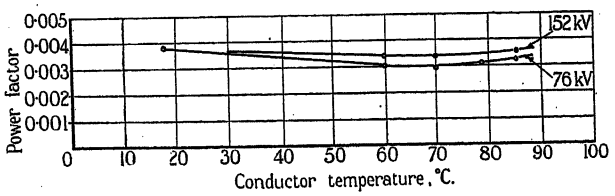


Fig. 17.—132-kV cable stability test, dielectric power-factor/temperature curve. Power factor measured at 50 c/s. Test on finished cable laid direct in ground. 1·1 × working voltage superimposed throughout the test. $S_{max} = 98$ kV/cm. Tests begun 17/7/35, ended 24/2/36.

Length tested:—175 yards.
Area of conductor:—0·2 sq. in.
Type:—single-core gas-filled.
Dielectric:—0·650 in.
Screen:—copper tape.
Voltage between phases:—132 kV.

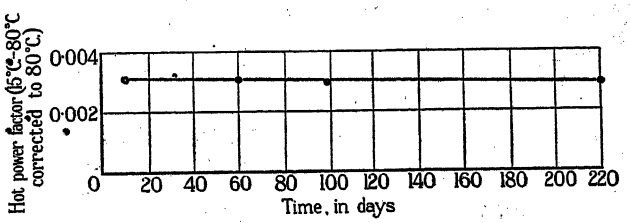


Fig. 18.—132-kV cable stability test, high-temperature dielectric power-factor records. Test details as for Fig. 17.

were plumbed into the lead at distances of 1, 2, 5 and 20 yards from this end.

A puncture was then made in the lead sheath at this end and readings were taken on the pressure gauges when steady values had been reached.

Fig. 19 shows the pressure/length relationship for this test and also the theoretical hollow-main curve for the particular feed pressure.

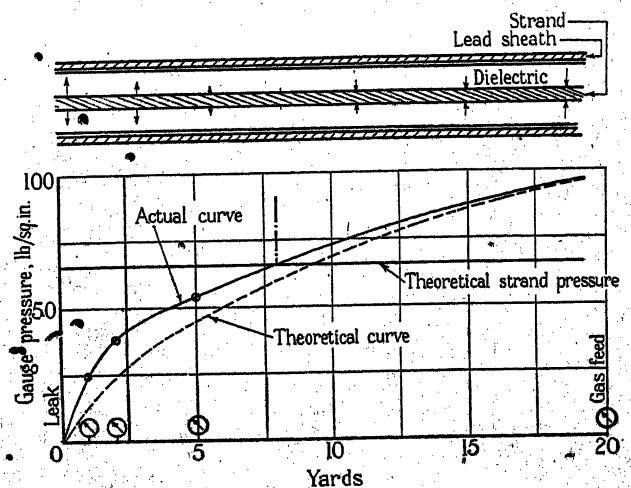


Fig. 19.—Gas-pressure/length curve for leaking cable.
P_1 = 113 lb/sq in abs.

An experimental check of the strand pressure was taken by connecting a pressure gauge into the strand of the length of gas-filled cable with a leak on one end, and a value of 77% of the feed pressure was obtained.

Further tests on two drum lengths of 132-kV cable with a joint between the lengths have given values of 67% and 71% of the feed pressure. In each case the strand pressure was measured at the leaky end so that the readings obtained were substantially those existing at the leak position.

For prevention of ionization at the conductor surface at 85 kV/cm it is necessary to have a pressure of about 90 lb/sq in absolute, allowing a margin of 20%, and hence a feed pressure of 90/0·7 = 130 lb/sq in absolute, assuming a figure of 0·7 for the ratio of the strand pressure to the feed pressure.

Considering the radial variation of the gas pressure at the leak section of the cable, and assuming that the thickness of the individual papers constituting the dielectric is graded uniformly as the radius of application, the pressure falls off approximately linearly with respect to the radius, i.e. from the strand pressure at the conductor to that of the atmosphere at the dielectric screen at the leak position.

Fig. 20 shows the gas-pressure/radius relationship at the leak for a feed pressure of 180 lb/sq in for a 132-kV 0·6-sq in single-core cable with 0·51 in radial dielectric, and also for a 33-kV 0·6-sq in cable with 0·14 in radial dielectric. On this Figure is also given the imposed electric stress/radius relationship and the corresponding gas-pressure values to suppress ionization. As can be seen, under leak conditions a limited portion of the outer layers of the dielectric will ionize. With longitudinal recession from the leak position, the pressure at the screen rises fairly rapidly to a value sufficient to suppress ionization.

In the above case it has been assumed for the most pessimistic view that the leak is large so that the pressure in the annulus at the leak position is equal to the atmospheric value. A restricted leak will result in a higher level of pressure in the cable generally.

It should be noticed that if gas is fed into a leaking feeder, then the gas flow is inversely proportional, *ceteris paribus*, to the distance between the leak and the feed point.

The gas-flow resistance of the annulus under the sheath (in a single-core cable) is not a very precise quantity. For a 132-kV 0·6-sq in cable the value is in the range of 10–100 lb/sq in per cu ft of gas per second, per yard of cable.

The radial gas-flow resistance of the dielectric between the conductor and the screen and also the resistance of the strand in a longitudinal direction are much more definite, and for a 132-kV 0·6-sq in single-core cable the former would have a value of 500 000 lb/sq in per cu ft gas per second multiplied by the length of cable in yards, while the latter would be 200 lb/sq in per cu ft of gas per second, per yard of strand.

(8.4) Location of Gas Leaks

The existing method of locating leaks consists in determining the direction of the gas flow at joints. To carry this out the domes are removed from the joint, the cross-feed pipe between domes is choked and then special domes having valves brazed into them are bolted on to the filling orifices. This process is carried out while the pressure is still on the cable system. Connections are made from the domes to an outside cross-feed pipe, having a valve to choke the passage, and also to a differential

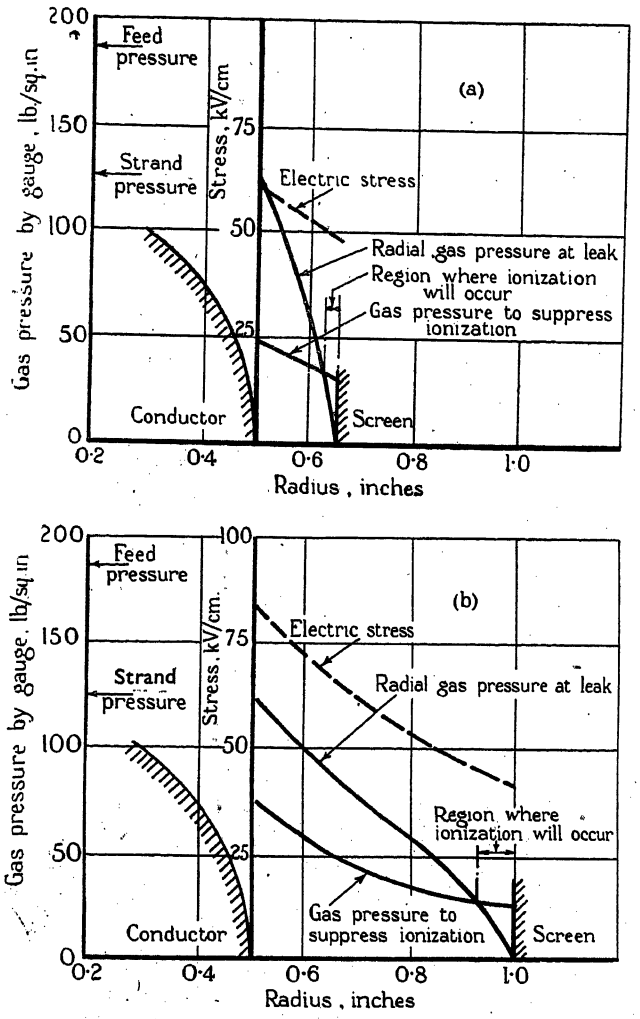


Fig. 20.—Radial gas-pressure variation and electric stress conditions at the leak section of the cable.

(*a*) 33-kV, 0·6-sq in cable.
(*b*) 132-kV, 0·6-sq in cable.

gauge to measure the pressure difference between the domes. The cross-feed pipe is choked so that a directional reading of the gas flow is obtained on the differential gauge. This process is carried out initially on the centre joint of the feeder and then on the quarter-length joint on the faulty side and so on until the leak is localized to a single length.

The joints at the ends of this length are tested and if the leak is not discovered on these the following cases have to be considered:—

(*a*) *The pressure-retaining sheath may be faulty and the outer sheath intact.* In this case the outer lead sheath is "ringed round," i.e. a ring of lead 1–2 in wide is removed at the joints and checked for emission of gas. If this is occurring the lead sheath is ringed at the centre of the length and then at the quarter-length position, and so on until the leak is localized to a short piece of cable.

(*b*) *Both sheaths of the cable may be perforated.* In this case, of course, no leakage of gas will occur from the ringed ends of the sheath, and a positive pressure is put on both ends of the second sheath and gas-flows established under the second sheath to the fault. Successive ringings of the outer sheath will again localize the fault to a short piece of cable.

(9) INSTALLATIONS CARRIED OUT

Up to the present, the total of gas-filled cables installed in this country comprises some 78 conductor-miles of 33-kV cable (all 3-core) and 25 conductor-miles of 132-kV single-core cable. An installation of 66-kV 3-core cable involving 9 conductor-miles is also proceeding. Some of the 33-kV cable has been laid on gradients of 1 in 4 over distances of 400 yards. A trial installation consisting of a 1-mile run of 132-kV 3-phase circuit has been in operation since December, 1937.

In the U.S.A. a 7-mile run involving 21 conductor-miles of 120-kV gas-filled cable of the pipe type was commissioned in December, 1941, while in Germany some installations of 33-kV gas-filled cable have been or are being installed, but the quantities are not known definitely.

(10) ECONOMIC AND TECHNICAL ASPECTS OF THE GAS-FILLED CABLE

There is no apparent technical limit to the use of the gas-filled cable for voltages up to at least 264 kV between phases. The lower voltage limit for the use of gas-filled cable depends, in the absence of any special requirements, on economic considerations. It may incidentally be noted, however, that the oil-filled cable is being used in certain instances for 33-kV systems, although the initial cost of this type of cable is not as low as that of the solid type. All the considerations leading to the use of oil-filled cable for 33 kV will apply at least equally to the gas-filled cable, which has the additional advantage of lower initial cost, absence of auxiliary apparatus, and greater simplicity of installation and operation.

For 66-kV working, which is the highest voltage for which solid-type cables of reasonable dimensions can be used, the gas-filled cable presents considerable economies in cost and dimensions. Compared with oil-filled cables for 66-kV and 132-kV working, the gas-filled cable possesses those advantages which have just been outlined with reference to 33-kV cables.

Referring to the question of special requirements, both the oil-filled and gas-filled types possess the advantage over the solid-type cable of not being detrimentally affected by local bad thermal conditions which may be present in the run of a cable system.

Another consideration which favours the use of gas-filled cable is that it is completely independent of gradients and the problems incident thereto, and can be run vertically for any height or depth without fear of physical or electrical trouble arising due to drainage of the impregnating compound and also without the necessity of altering the standard cable design in any way.

Yet another special requirement concerns the degree of fire risk involved in the case of cables laid in restricted spaces such as multiway ducts, tunnels, passages, etc. In the case of a fire originating in, or subsequently affecting, the cable, the presence of oil would add to the conflagration and the oil hazard of the cables has to be considered. This applies particularly in the U.S.A., where many such situations are encountered.

In the case of gas-filled cable, nitrogen would be emitted from any openings in the sheath and hence a fire would tend to be extinguished rather than supported.

(11) CONCLUSIONS

(*a*) The design of the gas-filled cable is based upon a quantitative appreciation of the electrical and physical requirements of the dielectric of a cable to withstand service conditions without deterioration, and definite margins of safety are provided and maintained.

(*b*) The manufacture of the cable does not involve the use of any novel or special plant or manufacturing processes other than

those which have already been in use for many years past in the manufacture of the solid-type cable.

(*c*) The cable system is free from external accessories and no special arrangement is necessary if the cable is run vertically for any height or distance.

(*d*) The economic aspect of the cable for the voltage range of 33–132 kV (inclusive) is good.

(*e*) The permittivity of the dielectric is a good deal lower than that of any other impregnated-paper dielectric.

(*f*) This is of importance in relation to the use, in the future, of higher-voltage and more highly stressed cables and the necessity of keeping the cable capacitance load on systems to a minimum.

(12) ACKNOWLEDGMENT

The authors' thanks are due to Messrs. W. T. Glover and Co., Ltd., for permission to publish the information contained in the paper.

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DISCUSSION BEFORE THE TRANSMISSION SECTION, 14TH APRIL, 1943

Mr. J. Hacking: This is the first paper which has been read before The Institution dealing with the high-pressure gas-filled cable, although it is the work done by the authors, together with the work of several other British firms, which has been largely responsible for the renewed interest in this subject in America as well as in this country.

The authors refer in their Introduction to the difficulties associated with solid dielectrics in high-voltage cables due to the ionization of voids in the insulation. It is owing to these troubles that manufacturers limit the maximum permissible conductor temperature on such cables to 65° C. When the design of the cable provides for the suppression of ionization it is present practice to permit conductor temperatures up to 80° C, and there is some reason to believe that even this figure is conservative. The possible economies which can be made are therefore twofold: first, a smaller section of copper can be used for the same load; and secondly, the thickness of dielectric can be reduced. So far as I am aware, oil-filled, compression, and gas-pressure or gas-filled cables are all capable of meeting the same dielectric stress and conductor temperature. Although the authors refer to all these types of cable, they make no reference to the type of cable in which gas is applied between the sheath and the dielectric, which has been developed by at least two of their competitors.

I question the authors' claim that pre-impregnated paper must be used to justify the title "gas-filled cable". American engineers use this term both for pre-impregnated paper and for bulk-impregnated paper with drainage.

The Central Electricity Board have extensive satisfactory experience with oil-filled cables for both 132 kV and 66 kV, the former being single-core and the latter both single- and 3-core. They have also satisfactory experience with 66-kV compression cables, both of the pipe type and of the self-contained type.

The Board have been in touch with the development work on the gas-pressure cable, and in 1936 they were asked by the authors for facilities for a trial installation under actual service conditions. As a result, the authors' firm laid a 1-mile loop of 132-kV cable in circuit with one of the Board's lines. This installation was put into service on the 4th December, 1937, and has been entirely satisfactory. As a result the Board have installed a total of seven short lengths of 132-kV cable of this type, four of them at line terminations, and when they were faced with the problem of laying a 132-kV cable through an important tunnel in which the fire risk was worthy of special consideration, they decided to employ the same type of cable. This installation has a route length of 6¼ miles, of which 1¼ miles is in the tunnel. The circuit has a capacity of 100 MVA and is made up of single-core cables, generally of 0·4-sq in section. This installation was put into commission in December last year, and has so far given satisfactory service.

The bulk of the paper deals with design problems associated with this particular type of cable, and the important question of economic justification has only a brief reference at the end of the paper. I should like to point out here that where alternative designs are technically sound and capable of meeting the service conditions the selection between them will be governed entirely by economic considerations. It would therefore help very much if cable makers would give comparative costs of the various alternative designs which are available for the different voltages.

The authors refer to the prospects of using gas-filled cables at 33 kV. There is, of course, very extensive and satisfactory experience with 33-kV cables of the solid type, which are technically satisfactory and are likely to continue to be used unless the cost of competing designs is less. This question will be affected by the number of lead sheaths to be used on the oil-filled or pressure cables, and I note that in Section 3.3.5 of the paper the authors suggest that the double lead sheath should be standard for gas-filled cables.

There is also extensive satisfactory experience with 66-kV single-core cables of the solid type. The relative costs are likely to be affected by the difficulty of using 3-core cables of the solid type on account of their large overall dimensions. There is less difficulty in using 3-core oil-filled or gas-filled cables.

There is a strong body of technical opinion which supports the view that pre-impregnated paper has inherently a lower impulse strength that bulk-impregnated paper. I have already mentioned that the Board have several installations of gas-filled cable directly in circuit with the lines and with these there has been no trouble. The experience is, however, limited and it is by no means unlikely that in the future the dielectric requirements of h.v. cables will be governed by the impulse conditions. I feel, therefore, that the relative impulse strengths should be fully investigated, preferably by some independent body (either the National Physical Laboratory or the Electrical Research Association); and I hope this is the type of development work which the authors say is proceeding on this aspect of the problem.

Mr. P. V. Hunter: In the authors' patent specification the impression is given that the main feature of their invention is a gas channel, to which remarkable qualities are attributed. No mention is made of those qualities in the present paper, because whereas the patent specification is intended for the use of the Patent Office the paper is intended to be read by electrical engineers, who know that in fact every pre-impregnated paper cable inevitably contains as many gas channels as it has paper tapes.

The authors, in seeking for their cable some patentable

feature, have claimed the gas channel associated with the use of gas pressure as an advantage. The paper when carefully studied shows, on the contrary, how serious is the limitation upon the design of the cable which is imposed by the presence of the gas channel. Fig. 3 shows the ionization stresses which exist for a 0·25-sq in single-core cable with 0·15 in dielectric at different values of gas pressure. The values indicated are extremely low, and will seriously limit the authors in the practical stresses which they can employ in the design of their cable. If progress is to be made in the manufacture of high-voltage cable, stresses must be used amounting to some multiple of those shown in Fig. 3. I fear, therefore, that their cable will not survive the competition of other types of cable which are not subjected to this limitation of ionization stress.

The authors are evidently a little worried about having chosen such a low factor of safety as 2, because in Section 3.3.4 they say: "It is necessary for the gas filling medium to be stable under electrical discharge since, under surge-voltage conditions, ionization or electrical discharge must occur in the gas-filled gaps within the cable dielectric." My comment on this is that if the factor of safety is correctly chosen there is no reason why there should be any electrical discharge in the gas-filled gaps. I think that, if Fig. 3 were drawn for an oil-filled cable, instead of the limit of stress at the conductor being 150 kV per cm it would be at least 450 kV per cm; so that the oil-filled cable starts with an advantage of 3 to 1 as compared with the authors' cable.

The authors have claimed consistently that "complete latitude is afforded by the nature of the impregnating process in the choice of the characteristics of the impregnating compound to meet the necessary electrical and physical requirements." I find that, on the contrary, the choice of materials which will satisfy the requirements of this cable is extremely limited. I have found only one, a very expensive pharmaceutical material, which can be relied upon to meet the requirements of this cable under the stresses that are proposed. Perhaps the authors will explain this more fully.

Mr. J. R. Beard: I am glad that we are to have on record in our *Journal* this important development of one form of gas-pressure cable. It shows that this country still maintains the technical initiative it has always had in respect of the development of h.v. cables.

I have been fortunate in having been closely associated with h.v. cable developments for nearly 40 years, including the first trial of the 132-kV gas-pressure cable described in this paper. When that trial was first suggested it was approached with a good deal of misgiving, but Mr. Beaver showed such encouraging results from his experimental work that doubts were largely resolved and, as the paper says, the trial has been an outstanding success. The most surprising thing was the answer to the original fear that the puncture of the sheath would result in a rapid reduction in gas pressure along the cable and the risk of extensive damage to the dielectric. This matter is dealt with fully in the paper, where it is shown how very local and limited such an effect is.

In any reference to 66-kV and 132-kV cables special tribute should be paid to the brilliant work of the Italian engineer, Emanueli, in developing the oil-filled cable and so providing sound and workable cables for use at these voltages at a time when the need for them arose. The large installations in many parts of the world, and especially in the London area, are a tribute to his engineering ability; but it seems probable that the simpler gas-pressure cable will largely supersede the oil-filled in the future.

The authors state that this type of cable can be made for voltages up to 264 kV between phases. What would be the dielectric losses at this voltage, and how would they affect the current-carrying capacity of the cable?

It would be of interest to have actual test figures for the impulse strength of both 132-kV and 66-kV cables and comparative figures for cables with other types of insulation. Would the authors suggest the fitting of lightning arresters on cables connected to overhead lines?

In Section 3.3.2 the authors state that as far as possible breakages are avoided in the inner layers of the paper dielectric, as if a joint is made the gas space which is formed is of at least twice the normal thickness. What happens if during the lapping of the insulation one of these inner tapes breaks? If under these conditions it is permissible to join the papers, does this not mean that there is a weak spot in this length of cable?

Why is the Hochstädter screen not taken right through the 132-kV joint, as it is on the 66-kV joint?

The major insulation of the 132-kV joint is a mixture of silk tape and impregnated paper tape. We have had no difficulty in obtaining perfectly satisfactory joints with 132-kV cable using paper only, and it would appear that unless absolutely essential it is better not to mix the dielectrics.

We have had a long-standing difference of opinion with the authors over their preference for a hard-setting bituminastic filling compound for joints and sealing ends where this is subject to electrical stress, as we have experienced a large number of breakdowns with this type of compound from 11 kV upwards. In the paper reference is made to filling with "high viscosity" bituminous compound. Does this mean that the authors have to some degree modified their views?

I suggest that every joint should be fully gas-pressure tested before the joint bay is refilled.

How frequently would the authors provide gas feeding stations? Would they merely be at the terminal points, irrespective of the length of the route?

The information with regard to gas-leak conditions given in Section 8.3 is interesting. As no gas feed can be given to the cable until someone can be sent to operate the necessary gas valves, how long would it be safe to leave the cable alive with reduced gas pressures in the cable?

Section 8.4 seems to suggest the need for very close localization of gas leaks. I think that if a leak were localized to a length of cable this would be sufficient, as it would probably be better to replace the length than to replace a shorter piece of cable and have to install additional joints.

I have left till last the all-important question of cost. The gas-filled cable should be inherently less costly than other types at high voltage, but the design of high-pressure gas-filled cable described in the paper seems to be unnecessarily expensive, and certainly for 66-kV 3-core cable with the same maximum stress the gas-pressure cable is not cheaper than oil-duct cable, as is stated in Section 10. It is possible that the cost might be reduced by giving consideration to the following points, and I should appreciate the authors' views on the possibility of adopting some or all of them.

After stranding, the conductor is passed through a die and then three metallized papers are applied. This treatment has not been found necessary on other types of cable working at similar maximum stresses, and the omission of this treatment should reduce the cost.

With the gas-filled cable the speed of lapping the pre-impregnated paper on the conductor is, I understand, very much lower than for normal-type cable insulation, and this has been put forward as one of the reasons for the higher cost of this type of cable.

The authors are strongly in favour of protecting the reinforcement of the lead sheath by means of a second lead sheath. This

is a practice which was favoured in this country when oil-duct cable was first installed, but experience with a single lead sheath on oil-duct cable indicates that satisfactory service will probably be obtained with non-ferrous reinforcement with standard waterproof coverings unless the ground conditions are bad either chemically or electrically.

A point directly bearing upon this question of cost is the maximum operating temperature. Makers have always stipulated a lower figure for solid-insulation cables than for oil-filled cables. The paper gives the impression that there is no need to make such a distinction with gas-pressure cables, and I should be glad of the authors' confirmation that they are prepared to operate gas-pressure cables at as high a temperature as oil-filled cables.

Dr. P. Dunsheath: I think that the general views of the authors on the application of precision calculations and deductions are open to criticism. The paper contains several examples of the application of mathematics where the first step in the manufacturing process would upset the whole of the theory. Take, for instance, Fig. 2, which shows a very nice lapping of papers of different widths, with different gaps and spaces between them, geometrically placed. What I should like to see would be another drawing, Fig. 2A, of the same section of cable and with measured gaps, taken from any sample of cable made on the machine to which this specification was given. This would reveal a very different story, and would invalidate many of the authors' deductions, because they depend upon an unattainable precision in the ratio of gap to thickness. In Section 1.1, for instance, we read that "the dimensions of the spaces . . . are complementary factors in the design"; and in Section 3.2.2, "if the width of the gas space is comparable with its thickness . . . the stress in the dielectric necessary to produce ionization . . . is higher." If these are fundamental factors in the design, and there is no cable-lapping machine which will produce that ratio, some care must be exercised in applying the theoretical principles.

The authors advocate the application over the conductor of metallized paper for screening purposes. If they had included some relative test results, (*a*) for cable made with a plain conductor, and (*b*) for cable made with metallized paper over the conductor, the case for screening would have been more convincing; but such a complicated construction is dangerous from the manufacturing point of view because it demands such expert supervision. Sooner or later the operator will leave a small piece of metallized paper sticking out where it should not be, with fatal results. Even Fig. 7 shows one of these metallized layers standing out into the dielectric. A simple conductor, carefully watched, kept clean, and if possible made smooth, seems preferable.

In Section 3.1.2 it is stated that "the pressure variation occurring between the maximum and minimum service temperature conditions imposes a minimum duty on the reinforced sheath." Is there not some confusion here between the requirements of the gas-filled cable and those of a cable in which gas pressure is maintained outside the lead sheath? In the latter case the sheath breathes "with variation of internal pressure"; but in the gas cable there should be no breathing. The duty on the sheath would appear to be that imposed by the maximum internal pressure only.

In Section 4.3 the authors say that the bursting distension of the sheath with the application of a test pressure of 100 lb per sq in should not be less than 5%. My experience would lead me to conclude that such a figure for the distension is not a function of the quality of the lead pipe but of the type of lead press used for making the pipe. An inferior pipe may easily comply with this specification, whereas a satisfactory pipe may fail to do so. One of the reasons for the difficulty is that when a lead pipe is burst in this way, the diameter at the centre of the burst is very much more than 5%, and the fact that it is so much more weakens the adjacent part, where the distension of 5% is measured. If a test of this kind is considered desirable it should be carried out within reinforcement of some kind, either in the actual reinforcement of the cable or in an enclosing steel pipe, which would limit the maximum expansion.

Section 8.3, analysing the variation in gas pressure along the space under the sheath and along the conductor, is very interesting, but here again care is necessary when drawing practical conclusions from the theoretical calculations. Even if the values of pneumatic resistance of the various components of the cable could be controlled with the accuracy suggested, the maintenance of an appreciable pressure at the conductor opposite a sheath puncture would not save the outer part of the dielectric from deterioration. The best thing to do with a leaky gas cable is to get it out of service at the earliest possible moment.

Dr. J. L. Miller: A considerable delay has occurred between the appearance of the present paper and the time when the authors initiated work on the gas-filled cable. This delay, however, may be considered to have served three useful purposes. First, it has enabled the authors to write with a sureness that can only be derived from a knowledge of the existence of a long period of satisfactory practical operation. Secondly, it has appropriately enabled the paper to appear just when great interest is being shown in gas cables in the U.S.A. It will consequently serve to enhance the prestige of British cable engineers and to remind everyone of the major contribution that the authors have made to high-voltage cable design. Thirdly, just when the interest in gas cables appears to be increasing generally in this country, the paper has shown what is practicable and proved in gas-filled cable technique up to 132 kV and what may be practicable at higher voltages.

I do not propose to make comparisons between the gas-filled cable and gas and oil cables of other types, but perhaps it is desirable to emphasize certain features which are of direct interest to the operating engineer. Thus, in the gas-filled cable it is evident that special precautions are unnecessary when it is installed on steep gradients, because it contains no free compound. Then, too, little auxiliary equipment is required, because gas-feeding apparatus is simple, and such equipment as pressure tanks is not wanted. Additionally, no undue dangers arise if an accidental puncture of the sheath occurs; warning can be given, the insulation is temporarily safe, and gas-leak location is relatively easy. Further, the cable does not require installation in ferrous pipes that might corrode under the influence of vagabond currents. Finally, the permittivity of the insulation is low. Other types of cables obviously have the above features in varying degrees—additionally, too, my assessment of them may not be beyond criticism—as well as additional ones that some engineers may consider desirable; but I feel that the combination of features present in the gas-filled cable, proved in the hard school of practice, must ensure its use in an ever-widening field.

The authors' interest in impulses is satisfying and the work they are doing is fully warranted. The problem, of course, is of great moment in the case of overhead lines and connected cables in the 200–300-kV class. Here, the lines will be freer from actual lightning flashovers than lower-voltage lines, but surges will certainly exist and they will be transmitted to the cables. It is obvious that a position where the lines were free from trouble and the cables were not, could not be tolerated, so that further development of very high-voltage cables must include impulse experiments.

As regards conductor screening, a recent American discussion

indicated disagreement on the question of its value in increasing 50-c/s electric strength, but showed more agreement on the point that screening improved the impulse strength. While careful consideration of the make-up of the various cables under discussion, together with one's own tests, can explain a great deal, it would be interesting to have the authors' views. In my opinion conductor screening is essential so far as the gas-filled cable is concerned.

Mr. R. E. Horley: The idea of the gas-filled cable is not a new one, for I remember that at the beginning of the war of 1914–18 a Russian engineer suggested the use of a single-core cable with a hollow conductor, in which he proposed to put compressed air. I am not sure, however, whether the air was intended to cool the conductor or to suppress ionization. The first patent of a gas-filled cable was granted in 1925, and the first patent of an oil-filled cable in 1926. To-day there are about 2 000 miles of oil-filled cable installed all over the world, whereas I doubt whether there are 100 miles of gas-filled cable. I am not suggesting that the merits of the two systems are in that ratio, but there is no doubt that the oil-filled cable has set an extremely high standard for high-voltage work. Very likely the success of the oil-filled cable has been partly responsible for the slow development of the gas-filled cable, because it may have made engineers hesitate to consider installing a cable with an internal pressure of 200 lb per sq in.

My company has been interested in oil-filled cable for many years, but it has also been interested in gas-filled cable, and has constructed cables of this type with pre-impregnated insulation and also with mass-impregnated insulation. We have had good results with both types, and have come to the conclusion it is not necessary to introduce peculiar features into the construction but that the standard methods of cable makers experienced in the manufacture of h.v. cable will be sufficient.

I am pleased to see that the authors have found a mathematical reason for using lower stresses on their 66-kV and 33-kV cables. I think this is advisable, seeing that these cables have to stand lightning surges. In my opinion the stress values which the authors mention are the correct ones.

Mr. G. N. Wright: Although the number of gas-filled cable installations which have been carried out so far is small, do the authors think that most of the teething troubles have been overcome? Have they any data regarding the length of time taken, per mile, for the first filling of the cable after installation?

A material which is reasonably immune from corrosion should be chosen for the reinforcing tapes, or the tapes should be given a suitable protective covering. While the outer lead sheath serves this purpose so long as it is intact, this sheath, without overall armouring, is somewhat vulnerable and may, particularly with the poor class of labour obtainable at the present time, receive unnoticed damage during laying. Further, in the unlikely event of the inner sheath developing a leak while the outer sheath is intact, may not restriction of gas flow between the two sheaths be sufficient to allow such a pressure to be built up as would burst the outer sheath, possibly at a point remote from the position of the leak on the inner sheath? If so, this is another point in favour of overall armouring.

No mention is made in the paper of the use of Freon gas. Has that idea been given up?

The authors' drawing of the sealing end shows no arrangement for core expansion. What is the reason for this omission? Further, why has porcelain, rather than a material of the bakelite variety, been chosen for the inner cylinder?

I am pleased to note that the permittivity of the dielectric proposed by the authors is lower than that of any other impregnated-paper dielectric, so that the capacitance is less than would otherwise have been obtained due to the physical dimensions of the cable. Further improvement in this direction would be welcomed by the supply industry.

Dr. L. G. Brazier: Since the Fisher–Atkinson patents were granted in 1925 the pressure cable has apparently been developed into a cable which in respect of cost is very competitive with other types. It is therefore very disappointing that so little progress has been made in the application of this type of cable to practical service conditions.

The present paper and the discussion thereon have made it clear that the modern gas-filled cable has an extremely dry dielectric. The air spaces are deliberately left, and the paper is actually scraped dry at a temperature of 100° C. This cable must therefore fall midway between the perfectly dry cable described by Arman* and the fully impregnated pressure cable. Its surge resistance is somewhat low, namely 800 kV per cm, while the thermal resistivity of 700 thermal ohms is on the high side. A more serious defect, however, is the low ionization voltage. Mr. Beaver only claims for the gas-filled cable an ionization voltage at twice working voltage as shown on the curve. It is, in fact, clear from the construction of the dielectric that this must be so and also, that, as the voltage is raised above this point, the ionization will be heavy. The other curves, however, show that even the ordinary solid-type cable has an ionization voltage greater than 3 times working voltage; the oil-filled cable has an ionization voltage exceeding 3 times working voltage; while the fully impregnated pressure cable has an ionization voltage exceeding 4 times working voltage.

Mr. T. R. Scott: About 15 years ago Emanueli announced the solution of the 132-kV problem by means of oil-filled cables. Since then many attempts have been made to produce alternative solutions. Some of these attempts have been successful, and the problem now is to select the most suitable and economical type for any given condition of operation. In the U.S.A., papers on some of these alternative types have been presented and discussed simultaneously, and some such procedure would appear to be necessary here in order to facilitate assessment. A discussion of this nature occurred at the Paris H.T. Conference in 1939, and with the up-to-date re-statement by the authors of the pre-impregnated gas-filled cable position the time would appear to be ripe for resumption of the general discussion.

Mr. B. Donkin: For the gas-filled cable, the 50-c/s pressure test is not of major importance, but further information on the surge strength referred to in Section 7.5 would be of great interest.

It appears from Section 3.3.1 that the design of the cable hinges on the allowable screen stress at the screen terminations in the joints and sealing ends. The type of joint illustrated in Fig. 9 has no screen and seems to embody much hand-applied insulation, requiring considerable skill and much time in its application. Would the authors give the approximate time required for making a single-phase 132-kV joint, and give the reasons for omitting the continuous screen over the hand-applied insulation?

A consideration of the gas-flow resistance, in Section 8.3, shows that it may take several days to charge a cable length of several miles to normal working pressure, even if gas is applied at both ends of the cable. This points to the desirability of gas-pressure sectioning, making, perhaps, each drum-length of cable a separate gas section. Somewhat elaborate arrangements have been made for indicating gas pressure, and even for automatically "topping up" with gas, in the event of leakage while the cable is in service. It is to be hoped that further experience will show that a great simplification, or possibly even a total elimination, of the gas-pressure alarms and automatic gas-charging can safely be effected.

* *Journal I.E.E.*, 1937, **81**, p. 625.

In the case of a long feeder consisting of a number of drum lengths, gas-pressure charging cannot normally be started until all the points and sealing ends have been finished, resulting in lengths of cable lying in waterlogged ground without gas pressure above atmosphere. Should the lead sheaths have been accidentally punctured, water will penetrate for an appreciable distance, owing to the essentially porous nature of the authors' design of cable. The orthodox fully-impregnated cable is much more resistant to the entry and penetration of water, because all the voids are practically filled with compound. This is a further reason for making each drum length a separate gas section, so that it may be jointed and put under moderate gas pressure immediately after being laid.

In Section 10 the authors refer to the superiority of the gas-filled cable in not being detrimentally affected by local bad thermal conditions, but it appears that this is true only to the extent to which the maximum designed operating temperature of 80° C is in excess of that (65° C) normally prescribed for fully-impregnated non-gas-filled cables. From the point of view of longitudinal heat conduction the gas-filled cable is no better than other cables. The maximum operating temperature of 80° C must be fairly close to the temperature of thermal instability: it therefore seems important to make a careful soil thermal-resistivity survey and also to install a hot-spot core-temperature indicator if the maximum safe loading is to be obtained without danger.

Mr. F. W. Main: I assume that the curves for the maximum and minimum stresses given in Fig. 5 are for solid-type cables. It would be interesting to draw a line through points corresponding to standard dielectric thicknesses for various working voltages.

Referring to Fig. 6, have the authors a curve for 1·75-mil 0·9 specific-gravity impregnated paper to make comparisons complete?

It is correctly stated in the paper that a cable dielectric consisting of paper fully and suitably impregnated is satisfactory in the absence of temperature fluctuations. As fluctuations under service conditions cannot be eliminated, ionizable gaseous spaces form, and the authors introduce a third element—gas maintained at high pressure. It is obviously necessary to take the precautions detailed in the paper in regard to the design of the dimensions and the positioning of the gas spaces, as well as in relation to accurate cable construction. To control successfully the complicated position created is an achievement, but, in employing reasonable dimensions of dielectric, the safety factor figure is only 2 compared with 4 for the compression cable.

Following the development of the original pressure cable, in which the pressure medium is not in contact with the dielectric but compresses it through a lead sheath, other cables containing gas either in the dielectric, or in direct contact with it but initially outside the electric field, have been developed, and the term "pressure cable" came to be applied to all h.v. cable propositions employing gas under pressure. Therefore, to avoid confusion, the original pressure cable has been renamed "compression cable": in the pipe-line type, the pressure gas is housed between the lead sheath and the wall of the steel pipe; and, in the self-contained type, between the diaphragm lead sheath and a further reinforced lead sheath. There are over 160 conductor miles of compression cable in actual service for voltages from 50 kV to 120 kV, the first installation at 66 kV having been in operation since 1932.

It is mentioned that, in the compression cable, low-pressure gaseous spaces are suppressed by the external application of gas pressure. This is partially correct. If the cable as manufactured is fully impregnated, and the authors agree that a cable can be made free from gaseous ionization up to high stresses, the external pressure maintains the dielectric in this condition under load fluctuations, and therefore the causes of ionization are eliminated rather than suppressed.

It is stated that to obviate disadvantages of accessory apparatus a type of cable is desirable in which the compensating arrangements are self-contained within the confines of the lead sheath. This is correctly claimed for the high-pressure gas-filled cable, but it is also true for the compression cable as all compensating arrangements are confined to the gas-containing sheath. The only apparatus, apart from that which is common to all pressure-type cables, is a vessel containing flexible metallic bellows for transmitting the pressure from the cable system to the oil in the sealing bells automatically catering for expansion and contraction.

The authors have, in the design of the cable, set out to prevent cold working of the pressure-retaining sheath. There is, however, no necessity for concern in respect of a limited movement of a good lead sheath; the lead-sheath diaphragm of the compression cable has been tested in various countries, and recent figures indicate that, taking the number of full-volume daily cycles per year as 300, a conservative estimate for the life of the lead sheath is 50 years.

In the event of a leak occurring in the gas-filled cable I should like to know how long it would take for the pressure to fall to that of atmosphere; for it is apparent that, when pressure is lost, the cable will have to be switched out of commission to avoid breakdown. Further, I should like to know what measures are taken to ascertain that pressure is distributed throughout the whole dielectric.

Mr. J. K. Webb: The paper should be read in conjunction with others recently published by the American I.E.E., and particular note should be taken of the discussion on these papers.*

Could the authors tell us what became of their ribbed-paper idea, described at the Paris H.T. Conference in 1939?† The method of screening the conductor now proposed, differs from that given in 1939; in this connection, how much trouble do the authors anticipate due to occasional creases in the metallized tape? My own experience has been‡ that when one attempts to smooth off the strand corrugations with metallized paper, the cure is often worse than the original complaint, since a single wrinkle in this paper is sufficient to wreck a whole length. The use of semi-conducting carbon-black paper has been suggested in lieu of metallized paper, as being easier to apply and less liable to pucker. Have the authors had any experience of its use?

Mr. A. W. Sweetinburgh: Reference is made at several points in the paper to comparisons with oil-filled cables, but it appears that the chief advantage claimed for the high-pressure gas-filled cable in this respect is on economic grounds. This in turn seems to arise from the absence of reservoirs and accessories. Fig. A shows the conventional design of an oil-filled cable section from this point of view. The upper and lower curves indicate the maximum transient pressure related to distance from the feed points, for heating and cooling conditions respectively. It is interesting to notice that the values of ordinates would decrease rapidly with time. This is particularly the case in regard to the expansion curve, as the viscosity of the oil in the central duct falls very quickly. Of course, the pressures indicated are only a function of length when oil is moved along the duct. If accommodation for expansion should be restricted, pressure changes of similar character would occur at all points.

* *Transactions of the American I.E.E.*, 1942, 61, pp. 652, 658, 719.

† "Developments in the Gas-filled Cable," Paris H.T. Conference, 1939, Paper No. 208.

‡ T. R. Scott and R. C. Mildner: "Long-period Ageing Tests on Solid-type Cables," *Journal I.E.E.*, 1939, 85, p. 67.

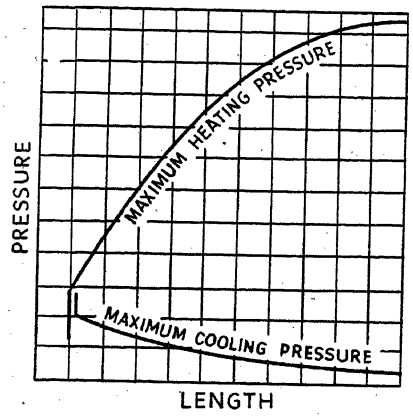


Fig. A

It is probable that the high initial rate of increase of pressure is due to the presence of free oil in the immediate vicinity of the conductor, where it is subject to the greatest rise in temperature, but after a short time oil is also fed into the central duct, and pressure curves of similar shape could be extended to provide for the movement of oil in the interstices and capillaries. In any case, some relief is soon available owing to the specific heat of the paper and to its elasticity in compression. During the early part of the heating cycle we have in effect a pressure rise at the core of a very strong cylinder. If such a system were sealed, this pressure would be transmitted radially somewhat slowly through the mass of the dielectric.

Referring now to the cooling cycle, which involves the risk of unduly low pressures and the consequent unfavourable conditions in the dielectric; it is clear that the main difficulty is that of ensuring the immediate return of the oil along the central duct, previously ejected. If this movement could be avoided it would be necessary only to provide for local pressure compensation, which would be favoured by the high temperature of the oil.

It may appear to be rash to suggest that such a system could operate when sealed, but there is some favourable evidence for this view. From extensive observation it has been found that both the range of transient pressures and the total oil displacement are less than anticipated. In one or two instances, by inadvertence, an oil section of cable has been operated for considerable periods through many load cycles, entirely sealed and isolated from oil reservoirs. The effects referred to in the Introduction to the paper have been in evidence, but to a surprisingly small degree. Breakdown has not occurred, and the cables continued to behave normally when matters were put right.

These considerations suggest that the moderate additional elasticity required could be provided within the cable and sheath system. The problem of ways and means appears to be less formidable than that which the authors of the present paper have solved.

Mr. D. T. Hollingsworth (*communicated*): It is believed that this is the first instance where, in a paper read before The Institution, the screen stress has been mentioned as a factor in the design of h.v. cables and joints. This is a particularly valuable point.

I am able to confirm that there is a minimum angle of taper adjacent to the core which can be cut by a jointer on the profile of a stress buffer cone; and consequently, if this operation is carried out on site, there is a limit to the screen stress which can be employed in the cable. This difficulty can be overcome by the use of paper rolls pre-cut to a definite profile in the factory. The jointer is supplied with a compound-impregnated roll of paper, the width of which is continuously tapered. When this roll is wound on to the core by the jointer, a profile is automatically formed which is, within practical measuring limits, exactly in accordance with the design. By this method of application it is possible to obtain a sufficiently small angle of taper at the core surface to ensure that a tangential stress of 2·21 kV per cm is not exceeded at the surface (this is for all normal cable-sizes). The angle of taper is smaller adjacent to the core than that used by the authors, but it is varied along its length, so that the tangential stress remains uniform with no increase in length. By using this method, even 33-kV cable can safely be designed with a conductor stress of 93 kV per cm compared with the figure of 65–75 kV per cm proposed by the authors.

I should like to refer to the authors' expression for the computation of the angle of lay for the reinforcement tapes. In deducing this expression it has been assumed that the lead sheath contributes towards the strength of the total reinforcement. Our experience has been that lead possesses no elastic modulus over a long period and that, consequently, it cannot contribute towards the total reinforcement. I mention this merely as a point of correctness, as it has only a small effect upon the angle at which the reinforcement tapes are applied to the axis of the cable.

It is further stated by the authors that the excess thermal expansion of the lead sheath during a temperature cycle produces a practical additional stress in the tape reinforcement. The lead sheath is a loose fit over the cable dielectric, and, for practical purposes, I should have thought that the lead sheath could be considered to be a fluid, so that the thermal expansion would produce only a distortion of the sheath towards the dielectric.

Mr. K. Konstantinowsky (*communicated*): I last met the present authors at the Paris H.T. Conference in 1937, not long after the question of producing a 110-kV cable had arisen in Prague. At that time, however, the high-pressure gas-filled cable was in the development stage and very little information or practical experience relating to it was available.

Whilst the number of installations carried out seems to be very promising, I take it that the paper was intended to give the experimental background as well. It seems to me that of the experimental work the most important is the ionization-stress/gas-pressure curve given in Fig. 3. Therefore, I would draw attention to the following points: The data in Fig. 3 are based on a cable with only 150 mils radial insulation, and the length of the cable tested is not given. The examples quoted in Sections 7.4.2 and 7.4.3 do not give any stresses comparable with those shown in Fig. 3, while no description of the specimen shown in Fig. 4 is offered and Fig. 6 refers solely to paper specimens. Are there any ionization data on 130-kV cable available, apart from the cable mentioned in Fig. 17, and, if so, how do they compare with those in Fig. 3?

Regarding Fig. 19 and Sections 8.3 and 8.4, when a leak occurs in the line there is a part of the cable, close to the fault, which will be ionized. According to Figs. 19 and 20 that part will be about 10% of the length in question on one side of the fault. From reading Section 8.4 the impression is formed that one section of the cable might comprise at least four, and possibly eight or more, cable-lengths; therefore such a section may be between 1 000 and 2 000 yd. In this case the faulty piece will be 200 yd long or even more. As ionization may take place in more than one length of the cable, do the authors suggest replacing two separate cable-lengths, or approximately 10% (or more), of the total section? What are their suggestions as to procedure in such circumstances?

In connection with this question I would point out that G. B. Shanklin found that his type of gas-pressure cable could be ionized

given for considerable periods and that self-healing would take place owing to the formation of wax during the ionizing process, this eventually extinguishing the ionization. I should like to know whether the authors experienced any similar occurrence with their cable and whether they rely on this self-healing process in the case of a cable under gas-leak conditions. How long does it take to locate the fault and to carry out the replacements?

Mr. H. E. Summers (*communicated*): The authors indicate the technical difficulties which are involved in the design of sealing ends where it is assumed that the tangential stress must not exceed 12 kV per cm. This limitation controls the magnitude of the sheath stress, and the authors suggest that this stress should not exceed 50 kV per cm for a practical design. Fig. 5 shows that for 33-kV cables designed to operate at this sheath stress, the maximum stress at the conductor must be reduced to approximately 69 kV per cm. It would appear that for 33-kV high-pressure cables the most efficient use is not made of the dielectric, and therefore, I suggest that consideration should be given to the use of a gas which will suppress ionization at a lower pneumatic pressure than nitrogen, thereby allowing a reduction to be made in the number of reinforcing tapes, or even the use of standard pre-impregnated solid-type cable.

If a solid-type 33-kV cable were designed to work at the conductor and sheath stresses mentioned above, it could be filled with Freon gas at a pressure of 25 lb per sq in and ionization would occur only if the working voltage were raised so that the conductor stress approached 100 kV per cm. Such a cable should be satisfactory as far as its electrical characteristics are concerned on any 33-kV system where the neutral point is either solidly earthed or earthed through a resistor; and arc-suppression coil earthing could also be employed if arrangements were made to short-circuit the coil after a short period of time (say 30 sec) following a fault. The use of Freon at a working pressure of 25 lb per sq in should be satisfactory since at the normal working temperature it liquefies at approximately 45 lb per sq in.

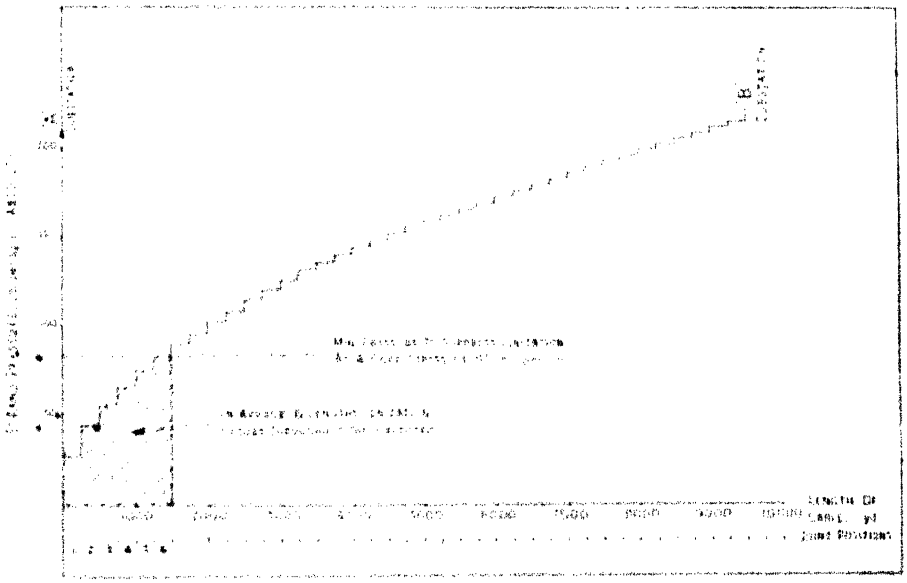


Fig. B.—132-kV 0·6-sq in gas-filled cable. Theoretical strand-pressure/length curve based on assumption that 3" equally spaced points are used and that strand permeable resistance is infinity. Lead sheaths punctured at "A" substation.

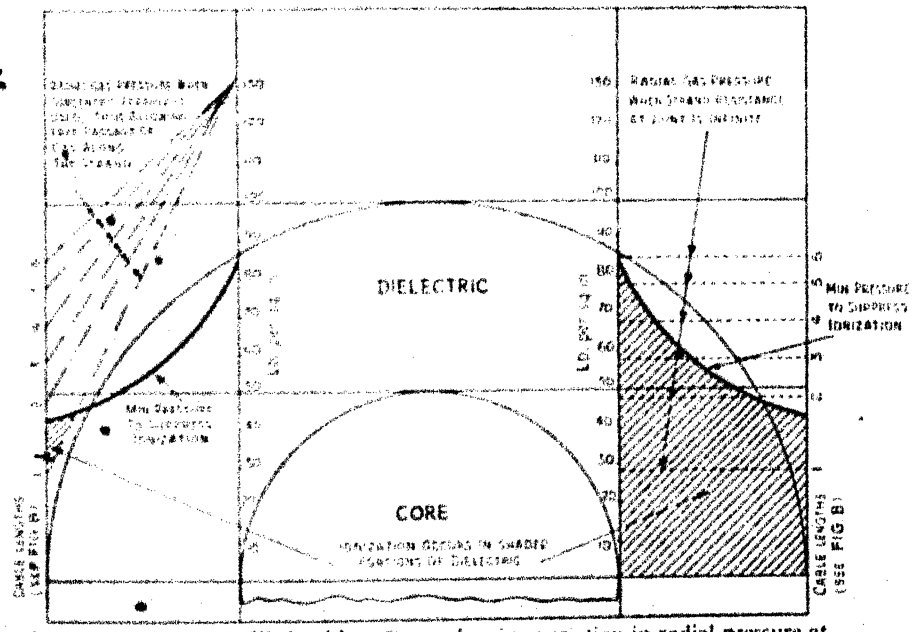


Fig. C.—132-kV gas-filled cable. Curve showing variation in radial pressure at the gas leak, and the cable lengths in which ionization occurs.

Freon-filled 33-kV cable would probably allow the cable to be run at a conductor temperature of 85° C. This would increase the current-carrying capacity of a solid-type cable by approximately 25%. This increase in rating would provide a considerable saving in raw materials, which is of importance under war-time conditions.

In Section 6.1.1 the authors state that the joint ferrule has been specially designed to preserve the continuity of the strand gas passage. I should like to stress the importance of this aspect, and, in order to amplify this remark, reference should be made to Fig. B, which indicates the strand pressures which are established when a fault occurs at one end of a cable system consisting of 9 500 yd of 0·6-sq in 132-kV gas-filled cable, equipped with automatic gas-feeding apparatus which maintains the terminal gas pressure under fault conditions at 200 lb/sq in. It should be noted from this curve that when the gas passage at the ferrule is completely restricted the strand pressure is no longer uniform. This condition allows cable sections Nos. 1 to 6, which are adjacent to the fault, to ionize.

Fig. C shows the radial gaseous and electrical conditions which are established in cable lengths Nos. 1 to 6, and it is clearly shown that the use of the ferrule which allows free passage of gas along the strand at the joint, only permits ionization to occur in the dielectric near to the sheath in the faulty section of cable (Section 1); whereas with the ferrule which restricts the gas flow at the joint, ionization occurs in all six sections of cable.

[The authors' reply to this discussion will be found overleaf.]

Messrs. C. J. Beaver and **E. L. Davey** (*in reply*): We propose to reply to the speakers in the order in which they took part in the discussion.

Mr. Hacking.

We did not refer to the type of cable in which the pressure is applied between the sheath and the dielectric because it has not yet been proved in service.

We agree with Mr. Hacking's point that the choice between technically sound cables is governed solely by economic considerations. These are definitely favourable to the type of cable under discussion.

Regarding the impulse strength of gas-filled cables, we would refer Mr. Hacking to our reply to Mr. Hunter. Ultimately we are agreeable to an investigation by some independent body of the behaviour of the cable under surges.

Mr. Hunter.

On the subject of design stress values we would say that it is possible to design a practicable 264-kV cable with a stress well within the range shown in Fig. 3.

Mr. Hunter refers loosely to a factor of safety of 2 for the cable, but this of course is the margin provided for the complete suppression of ionization at the working voltage and not the a.c. breakdown-voltage factor of safety, which is of the order indicated in Fig. 6.

Operating experience extending over 6 years confirms that the ionization margin provided is ample to avoid deterioration at the working voltage. We disagree with Mr. Hunter's remarks regarding the desirability of suppressing ionization in the gas-filled cable at voltages above twice the working voltage, for the following reasons: The only service voltages encountered above this limit are surge voltages, which may reach peak values of 8 to 9 times the working r.m.s. voltage on a 132-kV system. It is advantageous to allow ionization to occur in the cable dielectric under these conditions (provided no lowering of the surge strength of the dielectric results) since the dielectric losses produce attenuation and front-flattening of the surge.

The dielectric power-factor/voltage curve of a gas-filled cable is shown in Fig. D up to very high stresses, and very appreciable

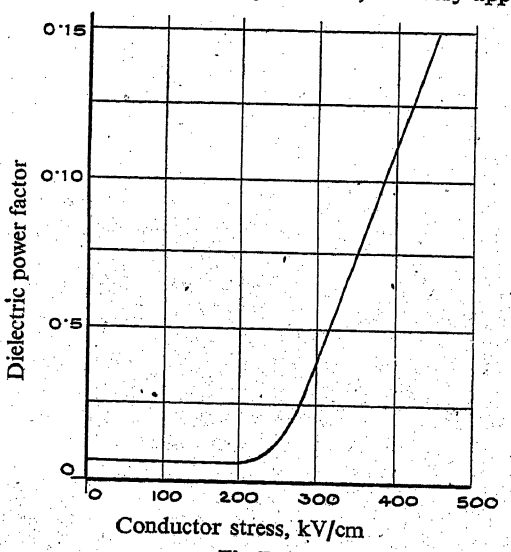


Fig D

effects can be predicted if these data are applied, in a manner suggested in a recent publication,* to the calculation of the attenuation of a voltage wave.

Fig. 6 demonstrates conclusively that the dielectric can withstand ionization under surge conditions without deterioration. The raising of the gas pressure in order to ensure a higher ionization voltage would result in very little, if any, improvement in the impulse strength, while the impressed surge would not be attenuated so much and the net result would be a lowering of the margin of safety from this aspect.

Mr. Hunter's query regarding the impregnating compounds is answered at the end of Section 3.3.3.

Mr. Beard.

On a 264-kV gas-filled cable the dielectric loss would reduce the current-carrying capacity by 7% to 8% for a trefoil circuit laid direct in the ground. It is not possible at present to give comparative impulse-strength figures for various types of cables.

We would recommend the fitting of lightning arresters on cables connected to overhead lines, especially where a short length terminates the line to, say, a transformer.

Some breakages of the inner tapes inevitably occur during the lapping operation, but our test cables were made under these conditions and have exhibited no sign of weakness.

The cores are screened on the 66-kV 3-core joint to eliminate the possibility of phase-to-phase faults, but as this possibility does not arise on the 132-kV single-core joint the compound has been utilized here as an insulating medium, thus reducing the maximum stress at the conductor and ferrule surfaces.

We have used a very high-viscosity bituminous compound in order to avoid high pressures being generated in the joints or sealing ends during thermal transients. These would add to the pressure duty of the accessories.

We would recommend gas feeding stations at distances of 2 and 3 miles in order that the charging process may be fairly rapid.

The cable can be kept alive until the gas pressure reaches 125 lb/sq in, and the time which would be needed for this to occur would of course depend upon the sizes of the leak and the cable system.

We have found it necessary to use the metallized papers at the conductor surface for the reasons given in Section 4.1, and in any case the cost of this screening is very small. The speed of lapping of the cable also has only a small effect on the cable cost.

We confirm that the gas-filled cable can be operated at as high a temperature as the oil-filled cable, namely 80° C.

Dr. Dunsheath.

The gas-filled cable does not depend upon precision of lapping to any greater extent than other types of cables. Regarding Dr. Dunsheath's remarks on the dimensions of the spaces, the thickness is the only dimension which is a fundamental factor in the cable design. We have clearly stated that the actual width/thickness ratios are well beyond the value necessary to influence the stressing in the gap. Our tests have proved that screening of the conductor is an advantage, and no trouble has arisen from defective application.

We agree that the duty of the sheath of a gas-filled cable is that imposed by the maximum internal pressure, and the design is such that this is kept at the lowest possible value.

Our extensive experimental work on lead pipes indicates that the bursting distension (which is directly related to the service duty of the sheath of a gas-filled cable) is a direct function of the pipe quality.

Dr. Miller.

We have described in other parts of our reply the development work we are carrying out with regard to the impulse strength of the cable.

We find that screening the conductor improves the 50-c/s electric strength but not the impulse strength.

* "Surge Phenomena" (E.R.A. Report Ref. S/T35, 1941).

Mr. Horley.

We are glad to know that Mr. Horley has had good results with gas-filled type cables.

Mr. Wright.

We think that the gas-filled cable system is now in an established position. The time required for the charging of 1 mile of 132-kV single-core gas-filled cable is approximately 1–2 days. It has for some years been a standard practice for single-core h.v. cables to be laid without armour.

We do not think that restriction of gas flow between the two sheaths is likely to cause trouble in the event of a leak developing on the inner sheath.

Our reason for not allowing for any core expansion at the sealing ends is that we cannot see why a sealing end should be treated differently from a joint. The amount of expansion that can be allowed for is relatively small and would be useless on a long run of cable. We have never experienced any trouble due to this arrangement, either on gas-filled or on solid-type cables.

Work on the possibility of using Freon for gas-filled cables has been held up owing to the difficulty of obtaining supplies in war time.

We have used bakelized paper experimentally for the inner pressure-retaining cylinder, but porcelain is definitely superior for the purpose.

Dr. Brazier.

Our reply to Mr. Hunter covers that part of the discussion in which the ionization-voltage value of the gas-filled cable is criticized.

Mr. Scott.

We hope that it will not be long before an opportunity occurs for a discussion of the merits of the different types of h.v. cables.

Mr. Donkin.

Regarding the 132-kV joint, the approximate time required for making this is 4 days; the reason for the omission of the screen is given in our reply to Mr. Beard.

With regard to the question of the maximum operating temperature for the gas-filled cable, we have run a stability test at 100° C conductor temperature without detriment.

Mr. Main.

The curve given in Fig. 5 depends solely on the geometry of the cable and not on the type of dielectric, but the values are clearly such as to refer to gas-filled or oil-filled cables.

We have no curve for 1·75-mil 0·9-specific-gravity paper yet, but hope to obtain one shortly.

The rate at which the pressure falls when a leak occurs on a gas-filled cable depends on the size of the leak and the internal volume of the gas-filled cable system, but in general if the pressure falls to 125 lb/sq in by gauge the cable should be taken out of commission.

It is clear that owing to the complete absence of free compound the gas pressure should be uniform throughout the cable, and all our tests have indicated that this is so.

Mr. Webb.

The ribbed-paper suggestion is being held in abeyance for the war period.

The method employed for screening the conductor is the same as that used in 1939, but in a diagram* which we published at that time dealing with an improved outer-screening metallized paper we showed only the outer screening paper.

We have obtained excellent results from the use of metallized-paper screens for the conductor, but have no experience of semi-conducting carbon-black paper.

Mr. Sweetinburgh.

We note Mr. Sweetinburgh's suggestions with regard to eliminating the accessories from the oil-filled cable system, but we are not qualified to comment upon them.

Mr. Hollingsworth.

In calculating the angle of lay for the reinforcing tapes it has been assumed that the lead sheath has no strength, but in calculating the thickness of the reinforcing tapes the inside diameter of the sheath has been taken, and no allowance made for residual tensile strength in the sheath.

We prefer to regard the lead sheath at, say, 40° C as a plastic solid which requires considerable pressure to cause it to flow or distort.

Mr. Konstantinowsky.

The results given in Fig. 4 are based on cable insulated with 150-mil dielectric.

Ionization tests on 132-kV cable with 1·75-mil papers at the conductor surface show somewhat higher ionization stresses than those given in Fig. 3.

From formula (4) and Fig. 3 it can be deduced that 3% to 4% of the length on one side of a gas leak will ionize in the outer layers, assuming that the exhaust pressure at the leak is at its lowest value, i.e. that of the atmosphere. The ionization at the fault position under these circumstances is not such as to damage the cable dielectric. The amount of replacement required would depend upon the nature of the leak. Extinction of ionization probably occurs in some cables on account of the generation of a gas pressure by the ionic bombardment of the oil, but this pressure cannot of course be generated in a cable which has a leak.

Mr. Summers.

We do not think it would be economic at present to design a gas-filled cable for operation with Freon at 25 lb/sq in by gauge, since it would be necessary to use gas-filled cable accessories, which are more costly than normal-type accessories, and the saving on the cable would be outweighed by the extra cost of the accessories.

We note with interest Figs. B and C in Mr. Summers's contribution to the discussion.

* "Developments in the Gas-Filled Cable," Paris H.T. Conference, 1939, Paper No 208.

THE MEASUREMENT OF WATER-HEATER DIVERSITY BY SUPERIMPOSED CONTROL*

By D. J. BOLTON, M.Sc.(Eng.), Member.†

(*The paper was first received* 18*th March, and in revised form* 21*st April,* 1943.)

SUMMARY

In certain areas, supplies have been furnished to storage water-heaters and other such loads through relays permitting the supply to be temporarily suspended by superimposed control during peak times at the discretion of the engineer. The tests described in this paper were carried out in two areas in which such methods of control were available. The tests were made independently of peak-time suspension, and were aimed at finding out how many heaters were consuming at any given time. For this purpose the supply was arbitrarily cut off from the heaters and resumed again as quickly as possible. The changes in the feeder load were then used as a measure of the heater load at that moment. By repeating the process at regular intervals it was possible to separate out the heater load curve from the curve for the remainder of the load, and thus determine the diversity of the water-heater load.

(1) INTRODUCTION

A precise knowledge of diversity is important in a number of cases, such as (*a*) size of supply gear to be installed, and (*b*) supply-cost calculations.

As regards (*a*), it is obvious that the sizes of distribution transformers and cables will be affected not only by the total kilowatts of apparatus connected but also by the load characteristics (i.e. diversity) of such apparatus. The correct sizes to install, whether governed by regulation or heating considerations, depend upon the maximum simultaneous load and can be predetermined only from a knowledge of diversity. In the case of transformers, mistakes can be rectified and a different size substituted when the one installed proves unsuitable. But a cable choice is irrevocable, and the appropriate selection is correspondingly important.

As regards (*b*), an analysis of the costs of electricity supply shows that only about one-fifth to one-tenth of the (pre-war) total is proportional to kilowatt-hours. The remainder consists of standing costs dependent partly upon the number of consumers but largely upon the maximum power demand which the consumer makes upon the distribution network and the bulk-supply point. The individual demand of each consumer, whether monthly or yearly maximum, can easily be measured, and in the case of many industrial and some commercial and domestic connections this reading is taken. But the precise incidence of this upon the system—i.e. the effective demand of a number of such consumers—depends upon the largely unknown factor of diversity. Its exact measurement, whether by simultaneous m.d. readings or by chart recorders, has generally been too expensive except for large-scale supplies or in occasional experiments on consumer groups, housing estates, etc.

It follows that most supply-cost calculations are far from scientific, and involve a considerable element of uncertainty. One has only to look at the wide divergence between the diversity estimates made for the same situation by different authorities to see how large this uncertainty is. Hence it is almost impossible to determine with any exactitude what is the actual cost of giving, say, an unrestricted domestic supply in any given area.

The matter has assumed great importance in recent years owing to the rigidity of the generation kilowatt charge, and owing to the disproportionate increase in the domestic load. This no longer merely modifies the industrial load peak; in many areas it sets up a predominating peak of its own. Post-war developments in space- and water-heating in such areas will be largely conditioned by estimates of diversity, and large-scale tests may then be found advisable.

In the meantime the technique of superimposed control enables us to take precise measurements of diversity in certain instances at very slight expense. The control system which makes this possible is a comparatively recent development, and whilst it is not suggested that the tests here described are the first of their kind, no such results appear to have been published hitherto. Most of the undertakings having the necessary equipment are either not at present using it in the particular way required for our purpose, or else are too fully occupied and too short-staffed to co-operate in tests at the present time. It is therefore reasonable to suppose that after the war, and with a probable increase in the number of such equipments, very many of these tests will be feasible and much valuable information will be gained.

Lest a too optimistic view be entertained as to the possibilities of this method of test, the following facts should be borne in mind:

(*a*) The tests are applicable only to apparatus operated by superimposed control. Ruling out such things as street lighting, whose load is known already, this means, in general, apparatus (such as water heaters, low-temperature radiators and storage cookers) capable of being temporarily disconnected without loss of service.

(*b*) Diversity has been described as a largely unknown quantity, but to a certain extent it is unknowable. Local habits and circumstances vary so greatly that any results must be scrutinized with the utmost care before they can be applied to another situation.

(*c*) War conditions make the work more difficult and the results less typical. The present domestic habits and time-tables are to some extent artificial and unrepresentative.

Notwithstanding these limitations it is felt that the method is sufficiently promising and sufficiently novel to be worth investigating, quite apart from the value of the actual results at present obtainable. A considerable part of this report is therefore spent in describing the procedure adopted in the two areas selected. Certain lessons have been learned, and are put on record for the assistance of future investigators.

In the national interest it is necessary to withhold the names of the areas from which current supply statistics were obtained. This is particularly unfortunate as it makes impossible a personal acknowledgment to those who have assisted. Tribute must, however, be paid, even though anonymously, to the two chief engineers who gave great help both in carrying out the tests and in furnishing much supplementary data.

(2) ORIGIN AND METHOD

The tests arose out of a suggestion made in October, 1940. In order to find out without unnecessary correspondence what installations were available, a number of makers of superimposed-

* Installations Section paper. Based on Report Ref. K/T105 of the British Electrical and Allied Industries Research Association.

† The Polytechnic, London. (Seconded to Ministry of Fuel and Power.)

control apparatus were approached. As a result 31 undertakings were written to—their installations comprising four different types of control system. In a few cases no reply was received and in 2 cases certain criticisms were offered; 13 undertakings offered co-operation after the war, and 7 were willing to carry out immediate tests. On pursuing the matter further, however, it was found that in most of these seven cases there were as yet no relays connected to heaters, and only two proved suitable for the purpose in view. The tests in these two areas (designated "A" and "B") were carried out in the winter of 1941 and repeated in the summer of 1942.

Both installations were of the "Actadis" pattern in which voice-frequency ripples are impressed on each of the distributors in turn, and thus operate tuned relays. These serve to open or close the switch supplying the controlled apparatus. The normal purpose of the installation when applied to domestic premises is to enable the supply engineer to cut off the controlled load at peak times and so reduce the supply costs, improve the regulation, etc. For test purposes the opening signal is arbitrarily sent out, and the load reduction is noted from the feeder ammeters. The closing signal is then emitted, and the rise in load is also noted. The whole process is repeated at suitable intervals throughout the test period, and thus a load curve of the controlled apparatus is picked out from the general load curve.

Since the purpose of the test is to investigate the normal state of affairs it is essential that this normal state shall not be appreciably disturbed by the test operation. Furthermore, it is important to keep down the aggregate time of interruption, or consumers whose storage is only just adequate will experience deprivation. The initial suggestion was that if the time between "off" and "on" signals were t minutes there should be a recuperation period of not less than $5t$ or $6t$ minutes before the next "off" signal was emitted. The correct ratio should really depend on the amount of use being made of the controlled apparatus at the time, but the results obtained in Area "A" suggest that this ratio is a satisfactory compromise.

The frequency of the test readings is therefore limited by the time t, and there appears to be a very great difference in this respect between the various installations. On ripple control systems the speed change of the ripple generator is sometimes carried out by means of a gearbox, and can only be operated when the generator is at rest. When the installations were first inspected the minimum value obtainable for t was 4 to 5 minutes in both cases, but in Case "B" the engineer was able to reduce this to half by electrical braking of the d.c. driving motor.

During light-load periods the number of readings obtainable on the basis of, say, $5t$ intervals is quite sufficient, but during heavy-use periods more frequent readings would be desirable, and this is just the time when it would not be safe to reduce the $5t$ ratio. Another reason for desiring frequent readings is to smooth out fortuitous variations. When the controlled load is only a small proportion of the total load on the feeder, fluctuations in the uncontrolled load are liable to make any single test reading unreliable. (It is believed that some other types of installation, employed in areas where co-operation after the war has been promised, are more suitable for this test, both owing to a shorter minimum time between "off" and "on" signals and because the signals occur simultaneously on all the feeders. With the type here tested the load changes are spaced out, and the changes in the ammeter readings are correspondingly harder to determine.)

(3) RESULTS

The figures for the two areas tested are summarized in Table 1, and the results are plotted in the form of graphs, Figs. 1 to 6.

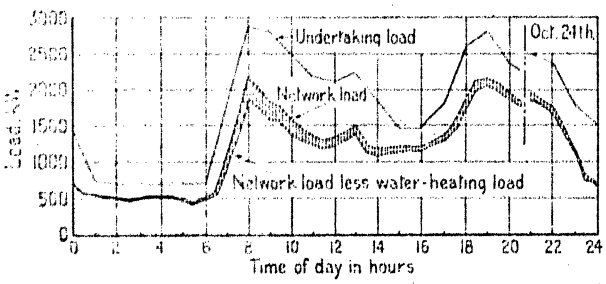


Fig. 1.—Area "A": load curves, 24th–25th October, 1941.

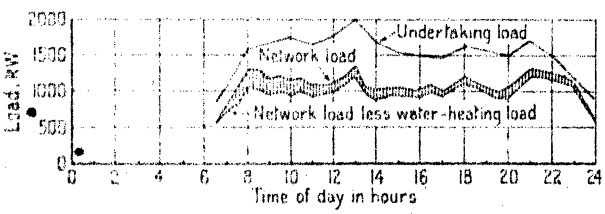


Fig. 2.—Area "A": load curves, 17th July, 1942.

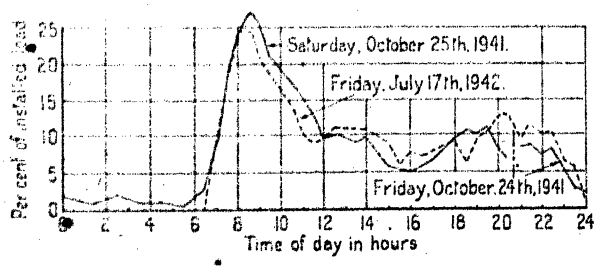


Fig. 3.—Area "A": incidence of water-heating load.

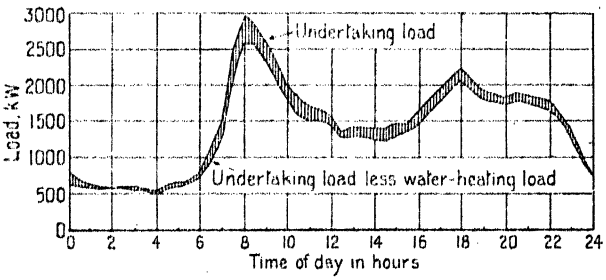


Fig. 4.—Area "B": load curves, 5th December, 1941.

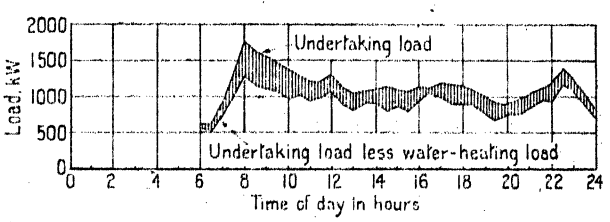


Fig. 5.—Area "B": load curves, 10th July, 1942

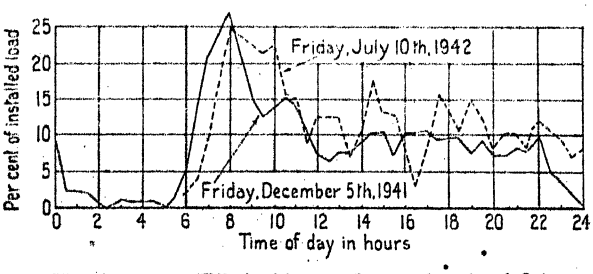


Fig. 6.—Area "B": incidence of water-heating load.

Table 1

PARTICULARS OF UNDERTAKINGS AND TESTS

Line		Area "A"	Area "B"
	Control equipment		
1	Minimum time between "off" and "on" emissions (t)	4 min	2 min
2	Readings taken every	30 min	15 min
3	Recuperation time between "on" and "off" (in terms of t)	$6\frac{1}{2}t$	$6\frac{1}{2}t$
	Consumer characteristics		
4	Type of dwelling	50% artisan dwellings 50% villas	Suburban villas
5	Approximate rateable value	£20 to £60	£40 to £50
6	Other data	—	80–90 % have telephone
	Heater characteristics		
7	Type	Circulator	Circulator
8	Supplementary to	Coal-fired back boiler, chiefly in kitchen	
9	Water capacity	13–24 gallons	30–40 gallons
10	Proportion fitted hand switch in series with thermostat	At least 75%	100%
11	Proportion lagged	50%	10%
	Test I Load data		
12	Number of heaters controlled	512	573
13	Loading of each	2 kW	3 kW (some 2)*
14	Total controlled load	1 024 kW	1 771 kW
	Test I Results		
15	Date	24–25 Oct., 1941	5 Dec., 1941
16	Day of week	Fri.-Sat.	Friday
17	Outdoor temperatures	36°–54° F.	51°–53° F.
18	Time of maximum load	8.30 a.m. (network only)	7.45 a.m.
19	Diversity at this time†	3·70	3·57
	Test II Load data		
20	Number of heaters controlled	555	696
21	Loading of each	2 kW	3 kW (some 2)
22	Total load controlled	1 110 kW	1 964 kW
	Test II Results		
23	Date	17 July, 1942	10 July, 1942
24	Day of week	Friday	Friday
25	Outdoor temperatures	55°–62° F.	60°–61° F.
26	Time of maximum load	8.15 a.m. (network only)	7.55 a.m.
27	Diversity at this time†	4·11	4·13
	Supplementary particulars		
28	Number of domestic consumers	5 865	5 377
29	Proportion of domestic to total consumers	92%	92%
30	Fixed charge of "all-in" tariff (per cent of rateable value)	20% and 15%	15% and 10%
31	Running charge of "all-in" tariff (per kWh)	0·55d.	½d. and $\frac{7}{16}$d.
32	Proportion of domestic consumers on "all-in" tariff, per cent of Line 28	29%	30%
33	Proportion of domestic consumers on prepayment meters, per cent of Line 28	34%	23%
34	Proportion of domestic consumers having electric cookers, per cent of Line 28	19%	12%
35	Proportion of domestic consumers having electric water heaters, per cent of Line 28	10%	19%
36	Total sales of undertaking (1941–42), millions of kWh	13·5	10·5
37	Proportion of domestic to total sales	87%	62%
38	Undertaking yearly load factor	27%	33%
	Difference between load shed and load acquired (Area "A" only)	Test I	Test II
39	Numerical average	16·1 kW	17·4 kW
40	Algebraic average	+ 2·44 kW	+ 3·8 kW

* One unit of 40–100 kW in Test I; not included in Test II.

† The actual diversities are slightly higher than shown because the readings taken include distribution losses, whereas the figures for the total controlled load do not.

Each line of the Table is numbered for reference purposes. The following are a few explanatory notes.

In both areas the first test was made over a 24-hour period and the second test from 6 a.m. to midnight. In each area the first two graphs refer to the two separate tests, and show the general load curve with and without heaters. The third graph shows the heater load only for the two tests together.

In Area "A" most of the water heaters are connected to two groups of single-phase supplies fed from pairs of Scott-connected transformers. To simplify matters the test was carried out on this single-phase network only. The figures in Lines 18, 19, 26 and 27 are for the load on these cables only, which is referred to as the network load. This, however, was only some three-quarters of the total undertaking load, and when the heater curve is compared with that of the whole undertaking a somewhat different picture is obtained.

In Area "B" there is no segregation, and all the figures and graphs refer to the whole undertaking.

(4) DIFFERENCE BETWEEN "OFF" AND "ON" READINGS

If the feeder load were steady apart from the water heaters, the load shed on interrupting the latter would always be slightly less than the load acquired on resumption. This is because, in the interval, certain thermostats will have cut in (due to cooling) whereas none will have cut out (due to heating) since the supply has been off. But this effect is likely to be masked by the far larger effect due to fluctuations of the remaining load. The chief advantage of taking both readings is therefore that they act as a check on each other, and so the load fluctuations can be to some extent averaged out.

The above reasoning is borne out by the results obtained in Area "A". Taking the first test, the numerical average of the differences between "off" and "on" readings (Line 39) is 16·1 kW. The algebraic average (taking account of signs) is + 2·44 kW, i.e. the load acquired is higher on the average by this amount. Evidently the chief cause of the difference is the fluctuation in the uncontrolled load, but there is a subsidiary cause and this latter is always in the same direction.

Now the true reading for the heater load (normal conditions) would be the load *shed* on interruption, and this might be obtained by averaging the two readings and then biasing the figures by an amount in the neighbourhood of 2 kW. Unfortunately the correct biasing figure would not be constant, and in the present instance (Area "A") a simple average of the two readings has been plotted. In Area "B" only one reading was taken, namely the load shed. (In this case the time between signals was only half as great.)

(5) COMMENTS ON RESULTS

An outstanding feature of all the water-heating load curves is the absence of any evening peak. The general shapes are similar in the two areas and both show little seasonal variation, though in Area "B" the summer load curve is about half an hour earlier than the winter curve.

The test did not concern itself with energy consumptions, but as a matter of interest the following figures were estimated from the areas under the heater load curves. Mean daily consumption per heater: Area "A" (2 kW loading), winter 3·9 kWh, summer 3·9 kWh; Area "B" (3 kW loading), winter 5·1 kWh, summer 6·6 kWh.

The apparatus under test consisted of circulator-type heaters used to supplement the service obtained from back boilers fitted to kitchen fires. Since the fires would not be maintained during the night and many of the tanks were unlagged, most of the heaters would be switched off by hand at night in order to save heat losses. This is borne out by a comparison of the summer and winter curves, which show that the coal fires in the winter do nothing to lessen the magnitude of the morning peak.

(6) CONCLUSIONS AND INTERPRETATION

The object of the test was to determine the diversity of a group of water heaters connected to a supply system. When such a group exists by itself the only figure of interest is the minimum diversity, i.e. that occurring at the heater peak. This value is given in Table 1, and was in the neighbourhood of 4 in each case. The figure can be interpreted by saying that with a group of heaters of this type and character of use the largest simultaneous demand can be expected to be about one-quarter of the total kW connected.

When the heaters form part only of the load connected to a cable or network, and/or when the network is part only of the total undertaking load, it is necessary to know the full shape of the heater load curve, not merely its peak value. The important figures then are the diversities at the times of network and system peak.

The curves show that in both areas there is only a negligible time differentiation between the heater peak and the uncontrolled load peak on the same feeder. (It should be emphasized that this result has relevance only to the particular type of heater tested, namely the circulator type which is switched off at night.) The "network diversity" is therefore substantially that already illustrated. In Area "A" this network forms only part of the whole supply system, and what may be called the "system diversity" of the water heaters would be that occurring at the undertaking peak time. In the present instance (Test 1) there are two almost equal peaks on the undertaking, namely that already considered (8 to 9 a.m.) and another at 7 p.m. At the latter time the water-heater load is less than half its maximum, and its diversity then is about 10. In the summer test (II) the undertaking peak is at 1 p.m. and the system diversity is about 9.

This point may be taken a little further, and with an eye to applications elsewhere. The two areas in this investigation are fairly small and relatively homogeneous. In both cases the load is largely domestic and from houses of a fairly uniform type (middle-class suburban). Larger undertakings will usually have a more varied type of load, but they will frequently include self-contained areas whose loadings are very comparable to the undertaking loads considered here. The present load curves should therefore be scrutinized with a view to the network and system peaks likely to arise in other areas.

Broadly speaking, in normal times there are three common peak times, as shown in Table 2. Opposite each are given the diversity values occurring at this time in the four sets of tests here made. (The effect of the war has been to reduce the likelihood of a late afternoon peak and to shift the probable times to the morning. This fact is reflected in the aggregate curves of the C.E.B., and in all Grid areas the winter peak now occurs between 8 a.m. and 12 noon, and is fairly constant throughout that period.)

(7) GUIDANCE FOR FUTURE TESTS

Tests of the above kind may be made to obtain information of purely local importance, or in order to provide data which will be useful elsewhere. In the latter case the following conditions may be laid down.

Tests are of very little use unless apparatus can be grouped so that all the heaters controlled by a given signal are of the same type and of substantially similar magnitude. Electric water heaters are broadly of two types, and the data required in each case are given in the succeeding paragraphs:

(*a*) Self-contained, fully lagged factory-made heaters, usually cylindrical, of capacity not exceeding 3 gallons for sink or basin,

Table 2

WATER-HEATER DIVERSITY AT VARIOUS PEAK TIMES

Time of day	Reason and character of peak	Diversities at these times			
		Area "A"		Area "B"	
		I	II	I	II
8–9 p.m.	Domestic heating and cooking overlap with lighting, traction and some power	3·8	4·3	4·8	4·2
12.30–1.30 p.m.	Domestic, largely cooking, especially Sundays	10½	9	14	9
5–6 p.m.	Domestic and commercial lighting overlap with power	13	12	10½	7½

and 15 to 30 gallons for bath use. This may be termed the "self-contained" type.

(*b*) Electric systems grafted on to fuel-fired installations, consisting of heater units with or without thermostats and with or without lagging, fitted to the storage tank or cylinder, which is usually larger than in (*a*) (say 20 to 50 gallons). This type of system is usually fitted with a hand-switch, even in cases where a thermostat is employed. It may be further split up as follows: (b_1) "Immersion" type employing horizontal heater near bottom of tank; usually intended for more or less continuous operation and lagged accordingly. (b_2) "Circulator" type employing vertical heater projecting down from top of tank, usually surrounded by tube to give quick heating of small quantities; frequently unlagged and usually switched on only as required.

In all cases it is essential to know the kW loading, the water capacity, and whether or not hand control is fitted, either in series with the thermostat or as a parallel circuit to a second heating element. Additional data which may be useful are the situation of the heater relative to the points of utilization, and details of the position of the heater element and the thermostat in the tank.

In Case (*a*) good lagging can be taken for granted, but in (*b*) the lagging should be classified according to whether it is good, medium, poor or absent. In Case (*b*) details of the firing should be obtained whether it is independent slow-combustion boiler, built-in kitchen range, or back boiler of coal fire. Its situation, whether in kitchen or living-room, should also be ascertained.

Besides the data for the apparatus the following points are important: day of week and time of year; atmospheric and feed-water temperatures; particulars of tariffs involved and the proportion of consumers on each; percentage of domestic consumers using cooking and water heating; extent to which feeder serves industrial as well as residential loads. Relevant data as to type of house, habits of consumers, travelling times and members in household; and whether frequent washing is required either by nature of occupation, atmospheric pollution or social habit. Particulars of home laundry activities. In Case (*b*) information is desirable as to whether the fire is kept going continuously, and if not the probable hours of lighting and extinction. When hand-switches are fitted an endeavour should be made to find out the probable time of "off" and "on" switching.

(8) ACKNOWLEDGMENT

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NOTES ON THE FLOW OF CURRENT BETWEEN ELECTRODES ON THE SURFACE OF A METAL PLATE OR TUBE*

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SUMMARY

The paper deals with the flow of current between point electrodes in circular and elliptical areas, a square, a rhombus, narrow and wide lenticular areas and a narrow lune. The flow between points on the surface of metal tubes is considered. Results obtained by the "six points in line" method are quoted. A collection of derived formulae is added.

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(1) INTRODUCTION

Measurements of the thickness of metal plates or tubes from one side only can now be made by a direct-current electrical method. In the "four points in line" method a low voltage is applied by point contacts to the surface and the potential drop between them observed. In B. M. Thornton's "six points in line" method[1] there are two pairs of points on which the potential is observed, and in Warren's "eight point" method[2] the electrodes are arranged in two squares. On account of the spread of the current the readings on the potential points differ, and their ratio is an indication of the thickness of the plate. The six- and eight-point methods give values for the thickness that are independent of the resistivity of the metal.

The theory of the flow of current between two electrodes in an infinite plate is well known, but the surfaces to be examined for thickness are in practice restricted in area and have boundaries which are not always of regular shape. The influence of proximity of the electrodes to a free edge has been previously examined.[3]

(2) THE EQUATIONS OF LINES OF FLOW IN AN INFINITE PLATE

Metallic structures which are exposed to air, or are designed to contain gases or liquids, are liable to corrosion and may become dangerously thin. Until within the last few years there had been no method in common use by which the thickness of a plate or tube or a casting could be measured with sufficient accuracy from one side only to determine whether thinning had occurred. Following a boiler explosion the problem became acute, and magnetic methods having been found to be unsuitable an attempt was made to solve it for thick plates or tubes by a simple electrical method. This was developed by B. M. Thornton and the author, and has since been extended to many cases of structures where thinning by corrosion or erosion or core shift has been suspected. It has been found possible to measure the thickness of steel plates or tubes up to 2 in thick, castings to 3 in, copper plates to $\frac{3}{4}$ in and aluminium alloys to 2 in (these being the maxima with which the authors have had to deal) with an average accuracy of $2\frac{1}{2}$ per cent.

An account of the method and of some earlier results obtained by it were published in December, 1938, in the *Proceedings* of the Institution of Mechanical Engineers.[1] The greater part of that work was done by a "four points in line" method. In this, two contacts are made with the surface under test by electrodes between which a direct current is passed. The current and the potential drop between exploring points near, but not too near, to the current contacts are observed and the results compared with those obtained on plates of known thickness and of the same material. The method is essentially comparative, though the results might be expressed in terms of resistance by calibrating the galvanometer used to measure the potential difference to read the microvolts usually met with. These readings depend on the manner in which the current is distributed in the metal and on the ratio of the spacing of the current contacts to the thickness of the plate. For thin plates, small spacings and currents give

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full-scale-deflections. Even with the greater thicknesses it has not been found necessary to use more than 15 amp on each current contact or a spacing of more than 9 in. The "spotlight" galvanometer has made it possible to incorporate the apparatus in portable form.

The ideal condition for a test of this kind is that of a surface so large that the boundaries do not influence the flow of the current. Most of the resistance in the path of a current diverging from point contacts is relatively close to them. In special cases it is important to know how the potential drop is distributed, and the following notes are solutions of problems which have arisen in the practical application of the method. They are chiefly concerned with the influence of the size and position of the electrodes on the potential gradient near them. Certain cases have been examined as examples of the influence of the shape of the specimen on the gradients in it.

The drop of potential at a point contact is theoretically infinite, and with finite contacts it is always large compared with that in the surrounding metal. The potential-exploring points must therefore be placed far enough from the current points for the gradient to be comparable with that in the rest of the metal under test. In the construction of standard resistors the position of the potential points is of the first importance.[4] In tests of the kind now considered it is sufficient that the current and potential points should be a fixed distance apart, as in the "ductor" contacts of Evershed and Vignoles, which have the advantage of a rotating movement when pressed on to the surface, by which a thin layer of scale or dirt is penetrated. The contacts in these heads are $\frac{1}{16}$ in apart.

(2.1) Derivation of Equation of Lines of Flow by Method of Conjugate Functions

The equipotentials V of the lines of flow between a source and a sink in a thin plane surface must satisfy the equation

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0$$

To find a general solution which makes V constant over the cross-sections or boundaries of the areas of contact of the current electrodes, assumed finite and circular, take real quantities U and V such that $(U + jV)$ is a function of $(x + jy)$, where j is $\sqrt{(-1)}$. Then

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} = 0, \quad \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} = 0$$

The curves $U =$ constant and $V =$ constant cut at right angles everywhere. When $V =$ constant is given different values the resulting curves are equipotential lines; $U =$ constant gives the curves of lines of flow. The problem is the same as that of the electrostatic distribution of field between equal electrodes, oppositely charged, or the flow of heat between points at different temperatures. The lines represented by U are, for a single line uniformly charged, radii spaced at equal angles apart, and the equipotentials are concentric circles. The lines of flow between a point source and a similar sink in a thin conducting surface are identical in form with sections of the field between two equal and oppositely charged linear conductors with axes at right angles to the surface.

The relations $U + jV = j \log (x + jy)$, or, in polar co-ordinates, $U = \theta$ and $V = \log r$, give the radial lines of force and the concentric equipotential circles for a single charged line conductor.

For two such lines spaced $-c$ and $+c$ from their mid-position,

$$U + jV = -j[\log (x + c + jy) - \log (x - c + jy)]$$

In polar co-ordinates, $U = \theta_1 - \theta_2$, $V = \log r_2/r_1$

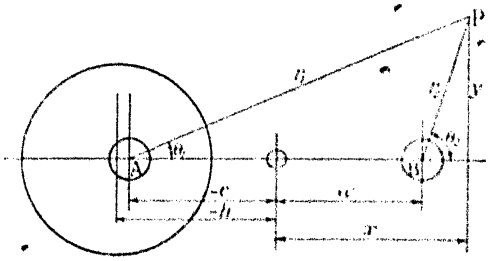


Fig. 1

The angle APB in Fig. 1 is given by $\theta_2 - \theta_1 = -U$

Now $$V = \log \frac{r_2}{r_1} = \frac{1}{2} \log \frac{(x + c)^2 + y^2}{(x - c)^2 + y^2}$$

and $$\frac{e^{2V} + 1}{e^{2V} - 1} = \coth V = \frac{x^2 + y^2 + c^2}{2cx}$$

and $$x^2 + y^2 + c^2 - 2cx \coth V = 0$$

This is the equation of an equipotential circle whose centre is at the point $(-c \coth V, 0)$ and whose radius is c cosech V.

Coth V is always greater than unity; writing $h = \coth V$, points at $(\pm h, 0)$ are the centres of circles of which the radii are $a = c$ cosech V and which are the equipotentials for selected values of V around the source and sink. Since the lines of flow are everywhere at right angles to the equipotentials they are circular arcs whose centres are on the transverse axis at distances $OQ = b$, from the origin, where Q is the point of intersection with the y-axis of a line drawn through A or B at right angles to the radius vectors defined by $U = \pm \theta$. Referring to Fig. 2,

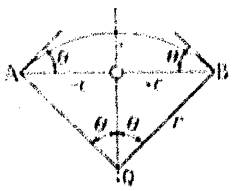


Fig. 2

the angle OAQ is equal to $\theta = \pi/2$. When the areas of contact are finite and of radius a, this being an exponential, $a = c$ cosech V_0, where V_0 is the starting potential. The current leaves the surface about A everywhere at right angles to it, but the curves of flow within the section of a start from the point $(-c, 0)$. In the section around B they converge to the point $(+c, 0)$, the centres of the sections now being at $(\pm h, 0)$.

(2.2) Derivation of Equation of Lines of Flow by a Physical Method

The above derivation of the equation of the lines of flow and equipotentials by the method of conjugate functions does not bring out the relation of the physical factors in the practical problem. The following interesting solution, for which the author is indebted to Dr. C. V. Drysdale, is simpler and more direct.

Let the plate have a thickness t and a resistivity ρ and let a current I be fed into it at point A (Fig. 1). The current flow will evidently be radial and uniformly distributed, and at a distance r from A the sectional area through which the total current I flows is $2\pi rt$. The current density is then $\Delta = I/(2\pi rt)$ and the electric force $E = \rho\Delta = \rho I/(2\pi rt)$. Hence the difference of

potential between two points P_1 and P_2 at distances r_1 and r_2 from A is

$$V_1 - V_2 = \int_{r_1}^{r_2} E dr = \frac{\rho I}{2\pi t}\int_{r_1}^{r_2}\frac{dr}{r} = \frac{\rho I}{2\pi t}\log\frac{r_2}{r_1}$$

If the distance between A and B is $2c$ the difference of potential between any point P at a distance r_1 from A and the mid-point O between A and B, due to the source at A, is

$$V_1 - V_0 = \frac{\rho I}{2\pi t}\log\frac{c}{r_1}$$

and if r_2 is the distance between P and B the p.d. between P and O is

$$V_2 - V_0 = \frac{-\rho I}{2\pi t}\log\frac{c}{r_2}$$

due to B. Since the current leaves at B the sign is negative. The net p.d. between P and O is therefore

$$V = (V_1 - V_0) - (V_2 - V_0)$$
$$= \frac{\rho I}{2\pi t}\left(\log\frac{c}{r_1} - \log\frac{c}{r_2}\right) = \frac{\rho I}{2\pi t}\log\frac{r_2}{r_1}$$

and for any constant value of V the point P must lie on an equipotential line for which

$$\log\frac{r_2}{r_1} = \frac{2\pi t}{\rho I}V = kV$$

where

$$k = \frac{2\pi t}{\rho I}$$

If $V = 0$, $\log\frac{r_2}{r_1} = 0$ or $r_2 = r_1$, so that the equipotential line is the transverse axis.

If x is the horizontal distance of P to the right of this line and y the vertical distance above AB, $r_1^2 = (c+x)^2 + y^2$ and $r_2^2 = (c-x)^2 + y^2$, so that

$$\log\frac{r_2}{r_1} = \frac{1}{2}\log\left(\frac{r_2}{r_1}\right)^2 = kV$$

and

$$e^{2kV} = \left(\frac{r_2}{r_1}\right)^2$$

Hence

$$\frac{e^{2kV}+1}{e^{2kV}-1} = \coth kV = \frac{x^2+y^2+c^2}{2cx}$$

or

$$x^2 + y^2 - 2cx\coth kV + c^2 = 0$$

This may be written

$$(h-x)^2 + y^2 = h^2 - c^2$$

where $h = c\coth kV$, and is the equation of a circle with centre "f" at $x = -h$ and $y = 0$, and of a radius a such that

$$a^2 = h^2 - c^2 = c^2(\coth^2 kV - 1) = c^2\,\mathrm{cosech}^2\, kV$$

so that $a = c\,\mathrm{cosech}\, kV$.

If V is positive and large, $\coth kV$ is only slightly greater than unity, so that $h = c\coth kV$ is a little greater than c and $a = (h^2 - c^2)^{\frac{1}{2}}$ is so small that the equipotential lines close to A are circles with A as centre. For smaller positive values of V, h and r increase as V decreases, but r is always less than h so that the circular equipotential lines are larger but shifted more to the left as V diminishes. Since $(h-x)^2 + y^2 = h^2 - c^2$ conditions are unaltered if both h and x are reversed in sign.

The lines of flow from A to B are circles with centre Q (Fig. 2) on the transverse axis. If OQ = b the equation of the stream-lines is

$$x^2 + (y+b)^2 = r^2 = b^2 + c^2, \text{ or } x^2 + y^2 + 2by - c^2 = 0$$

where

$$b = \frac{c^2 - x^2 - y^2}{2y}$$

(2.3) Graphical Construction of Field

The field can be constructed as follows (see Fig. 3): Let P, N, be the electrodes, O the mid-point between them, through which a transverse axis is drawn. Radii from P and N, spaced here $\pi/8$ apart, when produced to cut this axis do so in points which are the centres of circles defining the field. Thus, starting with a centre at O, a circle drawn through P and N cuts the axis at A and A′. With these points as centres, circles are drawn through

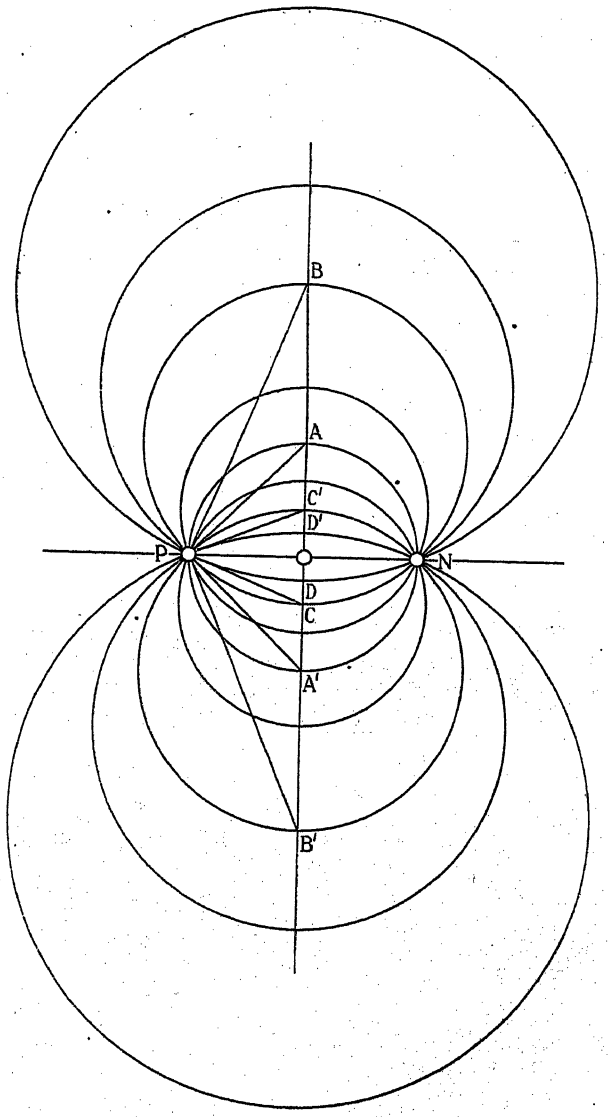


Fig. 3.—Graphical construction of field.

P and N cutting the axis at BB′, CC′. Circles with BB′ as centres give D, D′, and so on. If even sub-multiples of π are used, OP can be taken as the first radius, AP the next, then BP. The intermediate circles have centres at C, C′, D, D′ each corresponding to a sub-multiple angle of the original spacing. In this way the field can be drawn to any closeness of approximation. Vectors that are at right angles, such as PA, PA′ or PB, PC define by their intersections on the axis the diameters of the circles in which the right-angled triangles lie, e.g. AA′, BC.

(3) THE LENGTHS OF THE LINES; AND THE POTENTIAL GRADIENTS

The resistance of any element of the metal along a line of flow is directly proportional to its length and inversely proportional to its lateral spread between successive values of U. The radius r is given by $r = c$ cosec θ and the length of the arc AB, Fig. 2, is $l = 2\theta c$ cosec $\theta = s\theta$ cosec θ, where s = spacing $= 2c$. Thus for different spacings the lengths are as shown in Table 1.

Table 1

θ	0	30°	60°	90°	120°
θ cosec θ	1	1·047	1·208	1·57	2·42
If $s = 4$, $l = s\theta$ cosec θ =	4	4·18	4·83	6·28	9·68
If $s = 6$, $l = s\theta$ cosec θ =	6	6·28	7·24	9·42	14·5
If $s = 8$, $l = s\theta$ cosec θ =	8	8·37	9·66	12·5	19·3

The potential gradient along the line joining the contacts A and B is not uniform. The radius of the equipotential circles is $r = c$ cosech V, and V at a radius r is equal to arc cosech r/c.

The curve of Fig. 4 shows that the potential changes rapidly

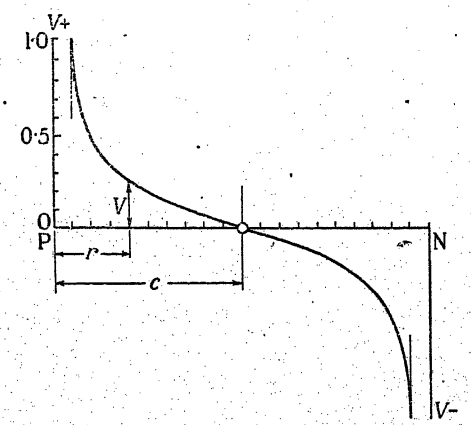


Fig. 4.—Variation of potential between electrodes.

near to the electrodes, and that it is nearly uniform over the middle third of the distance between them. The potential is taken as unity at $r = 0{\cdot}1c$.

The potential gradient $\dfrac{dV}{dr} = \dfrac{c}{r\sqrt{(c^2 + r^2)}}$

(4) THE TOTAL RESISTANCE BETWEEN ELECTRODES

The total resistance between line electrodes inserted at right angles to the surface, in a plate of unit thickness, can be calculated as before, by analogy with the electrostatic problem of the total flux between parallel electrodes of radius a spaced s apart, at voltages V_1 and V_2 respectively. The method is as follows:

By the principle of superposition,

$$V_1 - V_2 = (p_{11} - 2p_{12} - p_{22})E$$

where the potential coefficients p depend only on the size, shape and position of the conductors, and are defined as the potentials induced by unit charge, p_{11} on the first conductor, p_{22} on the second, p_{12} on the second by the first, p_{21} by the second on the first.

The current flow normal to any point on the surface of an electrode is $-\dfrac{1}{\rho}\dfrac{\partial V}{\partial n}$, the voltage falling along the outward-drawn normal; and the total flow from this electrode is given by

$$-\frac{1}{\rho}\iint\frac{\partial V}{\partial n}ds = \frac{1}{\rho}\iint\frac{\partial \psi}{\partial n}ds$$

where ψ is the electrostatic potential in the field. If E is the charge on this electrode, then the total flux (lines of force or lines of flow) from it is

$$4\pi E = -\iint\frac{\partial \psi}{\partial n}ds$$

The total flow of current in the current problem is $I = 4\pi E/\rho$. The total resistance in the current path is then

$$R = \frac{V_1 - V_2}{I} = \frac{\rho}{4\pi}(p_{11} - 2p_{12} + p_{22})$$

and $p_{11} = 2\log a = p_{22}$. If the source and the sink are at a distance S apart and have equal effective radii of contact a, then

$$R = -\frac{\rho}{2\pi}(2\log a - 2\log S)$$

or

$$R = \frac{\rho}{2\pi}\log\left(\frac{S}{a}\right)^2$$

Thus if $S = 6$ in and a is taken as 0·1 in, $S/a = 60$ and $\log (S/a)^2 = 8{\cdot}1$; with $\rho = 0{\cdot}7 \times 10^{-6}$ ohm per inch cube,

$$R = \frac{0{\cdot}7 \times 10^{-6}}{2\pi} \times 8{\cdot}1 = 0{\cdot}9 \times 10^{-6}\ \text{ohm}$$

Taking a as unity and keeping the ratio the same by raising S, the total potential difference $e = (\rho i/2\pi)\log S^2$.

Measurements made on a large plate of electrolytic copper $\frac{1}{2}$ in thick gave the readings shown in Table 2, at different spacings of the electrodes.

Table 2

S(in)	e (obs.) × 10^5	e (calc.) × 10^5
2	0·635	0·7
4	1·15	1·2
6	1·52	1·55
8	1·82	1·82
10	2·00	2·00

Here the value of S/a was chosen so as to give equal observed and calculated values at the largest spacing. It is evident that the conformation of the field remained in effect constant, contracting slightly at the lower spacings. The conclusion to be drawn from this close agreement is that the pointed electrode used led the current into the plate with very little distortion, as

if in fact it were a line electrode in the plate normal to the surface.

(5) CIRCULAR AND ELLIPTICAL AREAS IN A UNIFORM FIELD

Before considering further the influence of the size of the electrodes on expressions for the resistances and electric gradients in plates of various shapes, two cases of current flow may be given here with which the results to be obtained may be compared. When the flow is through circular or elliptical areas of relative resistivity ρ in a uniform current field, exact solutions are possible. In both areas the current density is the same at all points within the area. In the circular area, Fig. 5, the element

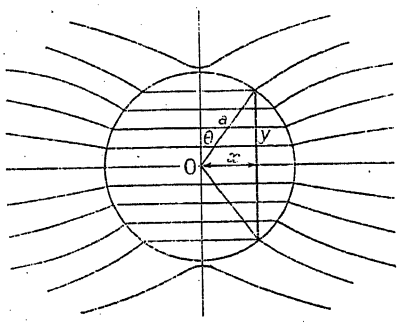


Fig. 5.—Circular area in uniform field.

of resistance $dR = \rho dx/(2y)$, the thickness of the disc and field being unity.

$y^2 = a^2 - x^2$ and $R = \int_0^a \frac{\rho dx}{(a^2 - x^2)^{\frac{1}{2}}}$ for the whole circle.

Thus $R = \rho \left[\arcsin \frac{x}{a} \right]_0^a = \frac{\pi}{2}\rho$, and this is the same whatever the size of the disc. The maximum drop of voltage along a strip of unit breadth is $2a\rho I/(2a) = \rho I$, where I is the total current crossing the transverse diameter. The potential gradient is a straight line.

In an ellipse, Fig. 6, when the flow is parallel to the major axis the element of resistance is $dR = \rho dx/(2y)$.

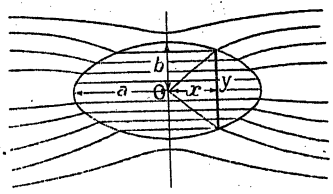


Fig. 6.—Elliptical area in uniform field.

Here $$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$y = \frac{b}{a}(a^2 - x^2)^{\frac{1}{2}}$$

and $$R = \frac{\rho a}{2b}\int_0^a \frac{dx}{\sqrt{(a^2 - x^2)}} = \frac{\rho a}{2b}\left[\arcsin \frac{x}{a} \right]_0^a$$

The total resistance for the whole ellipse is $R_p = \pi/2 \,.\, a/b \,.\, \rho$, which depends not on the size of the ellipse but on its proportions.

For an ellipse in which the flow is across the section parallel to the minor axis,

$$R_0 = \frac{\pi}{2} \cdot \frac{b}{a} \cdot \rho$$

The ratio $R_p/R_0 = a^2/b^2$. Thus the resistance of an ellipse in which the ratio of the axes is 5 to 1 is 25 times greater along the major axis than along the minor axis.

The total resistance of the square enclosing a circle is ρ; that of the circle is then $\pi/2$ times that of the square enclosing it.

The resistance of a rectangular strip of the same overall dimensions as the prolate ellipse is $\rho a/b$, and the ratio of this to that of the ellipse is again $\pi/2$, the same as for a circle, for any eccentricity of the area. The potential gradient is in this case a straight line everywhere, as for the circle.

The ratio of the current density in the area considered, which might be that of a copper rivet in an iron plate, or an elliptical inset, has been worked out and illustrated by the streamline method in a paper by Hele-Shaw and Hay.[5] The following examples are from the figures in this paper.

Example 1. *Circular Section.*—$\rho = 2{\cdot}0$; ratio of current densities $k = 1{\cdot}46$. With $\rho = 100$ the ratio is $1{\cdot}83$. Other closely approximate values are given in Table 3.

Table 3

Circle		Ellipse $a/b = 3$			
ρ	k	ρ	k	ρ	k
1	1·0	1	1·0	40	3·08
2	1·46	2	1·2	60	3·20
3	1·69	4	1·53	100	3·24
4	1·78	6	1·8	1 000	3·3
5	1·81	10	2·2		
100	1·83	20	2·7		

Example 2. *Elliptical Section.*—Ratio of axes 3/1; with $\rho = 20$ $k = 2{\cdot}7$; with $\rho = 100$ $k = 3{\cdot}24$; with $\rho = 1\,000$ $k = 3{\cdot}3$. From these values of k the concentration of flow in areas of these shapes can be found. In the electrical-current case k is the ratio of the conductivities of the areas to that of the surrounding metal; in the electrostatic case k is the ratio of the dielectric constants; in the magnetic case, the ratio of permeabilities; in the thermal case, of thermal conductivity; when in each case the respective constants of the surrounding medium are unity. k multiplied by the actual value of the constants in this medium gives the true flux through the areas.

(6) THE FLOW BETWEEN OPPOSITE CORNERS OF A SQUARE

In the divergence of a current from a cylindrical electrode of radius a to a concentric boundary of radius b the element of resistance at a radius r is

$$dR = \frac{\rho dr}{2\pi r}$$

and for the whole area

$$R = \frac{\rho}{2\pi} \log \frac{b}{a}$$

If the current passing is I the potential gradient is given by

$$g = \frac{-dV}{dr} = \frac{\rho I}{2\pi r}$$

The resistance of a sector element of angle α is $\rho dr/(r\alpha)$ and for the whole sector $\rho/\alpha \log b/a$.

When the electrodes are placed at the opposite corners of a square of side h the equipotentials near them are circles and the element of resistance then is $2\rho dr/(\pi r)$. The lines of flow cross the greater part of the mid-section at right angles, and their form is a compromise between the circles of unrestricted flow and radial flow with its hyperbolic gradient law. The variation from radial flow is not marked until the value of a is about $h/2$, and for the immediate purpose of finding the gradients near the electrodes the element of area at right angles to the lines of flow can be taken as $(\pi r/2)dr$. The current through it is I and the gradient

$$g = \frac{-dV}{dr} = \frac{-2\rho I}{\pi r}$$

Taking the radius of the electrode as $a = fh$ the gradient there, or at distances defined by f, is

$$g = \frac{-2\rho I}{\pi f h}$$

When the figure is a rhombus of acute angle α,

$$g = \frac{-\rho I}{\alpha r}$$

The current densities at points along the transverse diagonal are inversely proportional to the lengths of the lines of flow, and the ratio of these lengths to the side of the square depends upon the form that they take. This changes from the straight line between the centres of the contacts to the triangular path around the edge of the square. The streamline method of Hele-Shaw and Hay indicates that a sine-wave path is the closest mean approximation that can be made. Taking $y = b \sin x/a$ as the equation of the lines, their length is given by

$$S = 2\int_0^{\pi/2} (a^2 + b^2 \cos^2\theta)^{\frac{1}{2}} d\theta$$

where $\theta = x/a$.

Expanding and integrating, the relative current densities are found to be as follows (b is the distance from the horizontal axis along the other diagonal):

$b =$	0,	0·2,	0·5,	0·8
$\sigma =$	1,	0·98,	0·86,	0·71

The distribution of current over the section is then fairly uniform, except at the corners. The resistance between electrodes of radius a is approximately

$$R = \rho \cdot \frac{2}{\pi} \log \frac{h}{a\sqrt{2}}$$

(7) RESISTANCE OF A NARROW LENTICULAR ELEMENT

When the electrodes are circles at the ends of a lens-shaped element the lines of flow inside it are circles, but when the section is narrow an approximation can be made by taking the element of equipotential PP′, Fig. 7, to be a straight line. The coordinates of P are x, y; the length PM = PB − OA = $y - a$; $y = (r^2 - x^2)^{\frac{1}{2}}$, where r is the radius of the boundary; $a = r\cos\alpha$; and PP′ = $2[(r^2 - x^2)^{\frac{1}{2}} - r\cos\alpha]$. Let angle AOP be θ; then PP′ = $2r(\cos\theta - \cos\alpha)$.

The element of resistance at the chord PP′ is

$$dR = \frac{\rho dx}{2r(\cos\theta - \cos\alpha)}$$

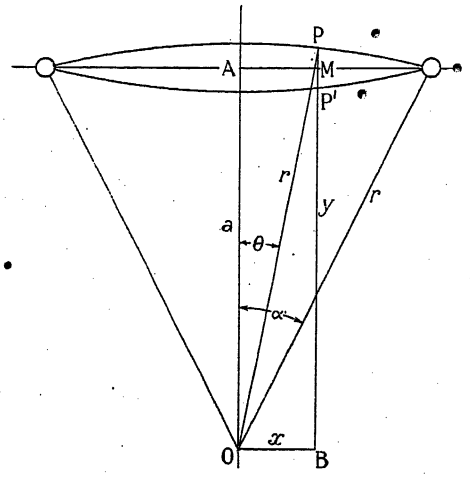


Fig. 7.—Determination of resistance of a lens-shaped element.

$$x = r\sin\theta, \quad \frac{dx}{d\theta} = r\cos\theta, \quad \text{and} \quad dR = \frac{\rho\cos\theta \cdot d\theta}{2(\cos\theta - \cos\alpha)}$$

Since at the limits when $\theta = \alpha$, the resistance is infinite, take the limits as $\pm\alpha'$ where $(\alpha - \alpha')$ is small. Then

$$R = \frac{\rho}{2}\int_{-\alpha'}^{\alpha'} \frac{\cos\theta d\theta}{\cos\theta - \cos\alpha}$$

The expression to be integrated can be transformed as follows:

$$\frac{\cos\theta}{\cos\theta - \cos\alpha} = 1 + \frac{\cos\alpha}{\cos\theta - \cos\alpha} = 1 + \frac{\cos\alpha}{2(\cos^2\theta/2 - \cos^2\alpha/2)}$$

$$= 1 + \frac{\cos\alpha}{2} \cdot \frac{\sec^2\theta/2}{1 - \cos^2(\alpha/2)(1 + \tan^2\theta/2)}$$

$$= 1 + \frac{\cos\alpha}{2\cos^2\alpha/2} \cdot \frac{\sec^2\theta/2}{\tan^2\alpha/2 - \tan^2\theta/2}$$

Integrating this expression, we obtain

$$R = \frac{\rho}{2}\int_{-\alpha'}^{+\alpha'} \left(1 + \frac{\cos\alpha}{2\cos^2\alpha/2} \cdot \frac{\sec^2\theta/2}{\tan^2\alpha/2 - \tan^2\theta/2}\right) d\theta$$

$$= \frac{\rho}{2}\left(2\alpha' + \frac{\cos\alpha}{2\cos^2\alpha/2}\int \frac{2dx}{a^2 - x^2}\right) \text{ where } x = \tan\theta/2 \text{ and } a = \tan\alpha/2$$

$$= \frac{\rho}{2}\left(2\alpha' + \frac{\cos\alpha}{2\cos^2\alpha/2} \cdot \frac{2}{2\tan\alpha/2} \log \frac{\tan\alpha/2 + \tan\theta/2}{\tan\alpha/2 - \tan\theta/2}\right)_{-\alpha'}^{+\alpha'}$$

$$= \frac{\rho}{2}\left[2\alpha' + \frac{\cos\alpha}{2\cos^2\alpha/2} \cdot \frac{\cos\alpha/2}{\sin\alpha/2} \log \left(\frac{\tan\alpha/2 + \tan\alpha'/2}{\tan\alpha/2 - \tan\alpha'/2}\right)^2\right]$$

$$= \frac{\rho}{2}\left(2\alpha' + 2\cot\alpha \log \frac{\tan\alpha/2 + \tan\alpha'/2}{\tan\alpha/2 - \tan\alpha'/2}\right)$$

$$= \rho\left(\alpha' + \cot\alpha \log \frac{\tan\alpha/2 + \tan\alpha'/2}{\tan\alpha/2 - \tan\alpha'/2}\right)$$

As an example, take $\alpha = 10°$ and give α' values 9°, 8°, 7°. The integral has then the value of the ordinates in Fig. 8. In the

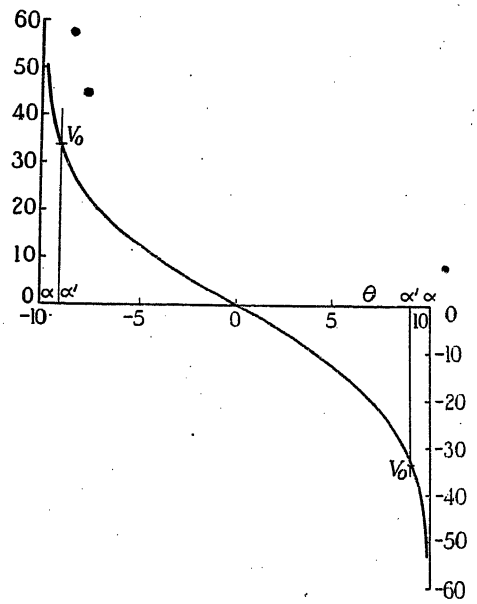


Fig. 8

middle half the change of resistance, and therefore the potential gradient, is nearly constant.

$$\frac{dR}{dx} = \frac{\rho}{2r} \cdot \frac{1}{\cos\theta - \cos\alpha}$$

Thus dR/dx is a minimum when $\theta = 0$ and would be infinite if $\theta = \alpha$.

(8) RESISTANCE OF WIDE LENTICULAR SECTIONS

When the defining angle α is relatively large, though less than unity in circular measure, the equipotentials in sections of this

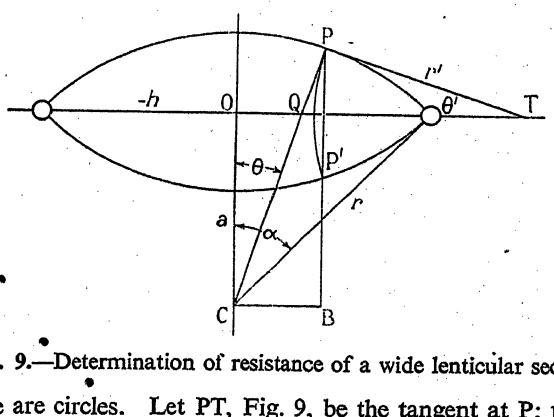


Fig. 9.—Determination of resistance of a wide lenticular section.

shape are circles. Let PT, Fig. 9, be the tangent at P; the arc with T as centre is then the equipotential line.

$$CQ = a\sec\theta = r\cos\alpha\sec\theta$$

$$PQ = r(1 - \cos\alpha\sec\theta)$$

and $$r' = PQ\cot\theta = r(\cos\theta - \cos\alpha)\operatorname{cosec}\theta$$

The element of resistance dR is given by

$$dR = \frac{\rho dr'}{2r'\theta} = \frac{\rho dr'}{2r\theta(\cos\theta - \cos\alpha)\operatorname{cosec}\theta}$$

the thickness of the plate being unity.

$$\frac{dr'}{d\theta} = r\operatorname{cosec}^2\theta\,(\cos\alpha\cos\theta - 1)$$

and $$dR = \frac{\rho}{2\theta} \cdot \frac{1}{\sin\theta}\left(\frac{\cos\alpha\cos\theta}{\cos\theta - \cos\alpha} - \frac{1}{\cos\theta - \cos\alpha}\right)d\theta$$

$$R = \frac{\rho}{2}\int_{-\alpha'}^{+\alpha'} \frac{\cos\theta\cos\alpha d\theta}{\theta\sin\theta(\cos\theta - \cos\alpha)} - \frac{\rho}{2}\int_{-\alpha'}^{+\alpha'} \frac{d\theta}{\theta\sin\theta(\cos\theta - \cos\alpha)}$$

Expanding the harmonic terms and retaining the first two terms of each series (the error introduced by omitting the higher terms is about 3 per cent), knowing that θ is less than unity, we have, to this approximation,

$$R = \frac{\rho}{\alpha^2\alpha'}\left\{1 + 2\left[1 - \left(\frac{\alpha'}{\alpha}\right)^2\right]\cos\alpha\right\} - \frac{\rho}{4\alpha^3}\log\left(\frac{\alpha + \alpha'}{\alpha - \alpha'}\right)^2$$

The gradients in the wider lens are slightly greater at the electrodes than in the narrow case for the same total drop of potential.

(9) RESISTANCE OF A CIRCULAR DISC ACROSS A DIAMETER

The thick lenticular element is intermediate between the thin case and the circular disc considered next, for which an exact solution can be obtained.

The lines of flow and the equipotentials are circles. When h

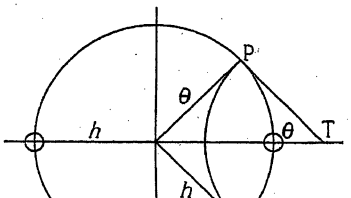


Fig. 10.—Determination of resistance of a circular disc across a diameter.

is the radius of the disc the radius of an equipotential circle r is $h\cot\theta$, θ defining the point P (Fig. 10).

$$dR = \frac{\rho dr}{PP'} = \frac{\rho dr}{2r\theta} = \frac{\rho h\operatorname{cosec}^2\theta d\theta}{2h\theta\cot\theta}$$

Thus $$R = \int_{\theta_a}^{\pi - \theta_a} \frac{\rho d\theta}{\theta\sin 2\theta}$$

where $\theta_a = \arcsin a/h$ and a is the radius of the small electrode area whose centre is on the rim of the circle.

The solution is[6] $$R = \frac{2\rho}{\pi}\log\frac{2h}{a}$$

(10) RESISTANCE OF AN ELLIPTICAL PLATE WITH END CONTACTS

When the area is an ellipse and the lines of flow are taken to follow those at the boundary the equipotentials are confocal hyperbolas and the solution may be obtained by the use of special functions; but, by symmetry with the above solution, the resistance must have the form

$$R = \frac{2\rho}{\pi}\log\frac{2a^2}{bc}$$

where a is now the semi major axis and b the semi minor axis, c is the radius of the area of contact with its centre on the rim.

In both the circular and elliptical cases the change of resistance

as the area of contact is increased, or between equipotentials, is of the form shown in Fig. 8.

The above results may be compared with those given in Section 5 for circles and ellipses in a uniform field. The resistance as defined there is $(\pi/2)\rho$ for the total circle and $\frac{\pi}{2}\cdot\frac{a}{b}\cdot\rho$ or $\frac{\pi}{2}\cdot\frac{b}{a}\cdot\rho$ for the ellipse, according as the flow is along the major or the minor axis.

(11) RESISTANCE OF A NARROW LUNE

The area is defined by the angles α_1 and α_2 on a base $2h$ (see Fig. 11).

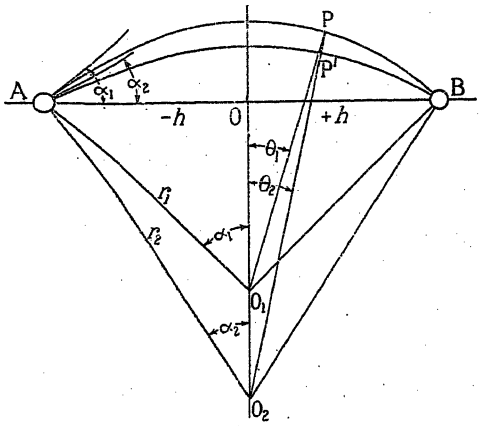


Fig. 11.—Resistance of a narrow lune.

$$OO_1 = h\cot\alpha_1,\quad OO_2 = h\cot\alpha_2$$

The radii of the boundaries are r_1 and r_2.

$$O_1O_2 = c = h(\cot\alpha_1 - \cot\alpha_2)$$

The resistance $$R = \rho\int_{-\alpha'}^{+\alpha'}\frac{rd\theta}{PP'}$$

The maximum width of the area is $r_1 + c - r_2$, and the mean radius $r = (r_1 + r_2)/2$.

$PP' \simeq r_1 - r_2 + c\cos\theta$, where $\theta = (\theta_1 + \theta_2)/2$. When $\theta = (\alpha_1 + \alpha_2)/2$, $PP' = 0$, and $(r_2 - r_1) = c\cos\alpha$, where $\alpha = (\alpha_1 + \alpha_2)/2$, we have

$$PP' = (r_2 - r_1)\cdot\frac{\cos\theta - \cos\alpha}{\cos\alpha}$$

$$R = \rho\frac{r_1 + r_2}{2}\int_{-\alpha'}^{+\alpha'}\frac{\cos\alpha d\theta}{(r_2 - r_1)(\cos\theta - \cos\alpha)}$$

$$= \frac{\rho}{2}\frac{r_1 + r_2}{r_2 - r_1}\cdot\cos\alpha\cdot\frac{1}{2}\int\frac{d\theta}{\cos^2\theta/2 - \cos^2\alpha/2}$$

$$= \frac{\rho}{2}\frac{r_1 + r_2}{r_2 - r_1}\cdot\frac{\cos\alpha}{\cos^2\alpha/2}\cdot\frac{1}{2}\int_{-\alpha'}^{+\alpha'}\frac{(\sec^2\theta/2)d\theta}{\tan^2\alpha/2 - \tan^2\theta/2}$$

$$= \frac{\rho}{2}\frac{r_1 + r_2}{r_2 - r_1}\cdot\frac{\cos\alpha}{\cos^2\alpha/2}\cdot\frac{1}{2\tan\alpha/2}\cdot\log\left(\frac{\tan\alpha/2 + \tan\alpha'/2}{\tan\alpha/2 - \tan\alpha'/2}\right)^2$$

$$= \frac{\rho}{2}\frac{r_1 + r_2}{r_2 - r_1}\cdot\cot\alpha\,.\,2\log\frac{\tan\alpha/2 + \tan\alpha/2}{\tan\alpha/2 - \tan\alpha'/2}$$

$$R = \rho\frac{r_1 + r_2}{r_2 - r_1}\cdot\cot\alpha\,.\,\log\frac{\tan\alpha/2 + \tan\alpha'/2}{\tan\alpha/2 - \tan\alpha'/2}$$

The gradient is nearly the same as that of a thin lenticular area but is slightly less at the electrodes (see Fig. 8).

(12) INFLUENCE OF THICKNESS OF PLATE ON DISTRIBUTION OF CURRENT

Whether for the purpose of a test a plate can be regarded as thin or thick is largely a question of the distance the contacts are placed apart. For a spacing of 2 in a $\frac{1}{2}$ in plate might be considered to be thick, but for a 6 in spacing thin, so far as it affects the potential at any point. When, as in thin plates, the current density σ at a point on the transverse axis of Fig. 2 can be taken as inversely proportional to the length of the current line passing through the point, the manner in which σ decreases as the field spreads can be indicated by taking the current density σ_0 at the origin as unity and calculating $\sigma = \sigma_0 s/l$, where s is the spacing of the electrodes. The length of the arc starting at an angle θ to the line AB, Fig. 1, is $2\theta c$ cosec θ, or $s\theta$ cosec θ. Some of these values have been given in Section 3. Table 4 gives the

Table 4

θ	0°	30°	60°	90°	120°	150°	180°	210°	240°
σ	1·0	0·96	0·86	0·63	0·42	0·29	0·23	0·2	0·18

relative values of σ at points where the curve starting at an angle θ cuts the transverse axis.

These are drawn in Fig. 12, and experimental values are also

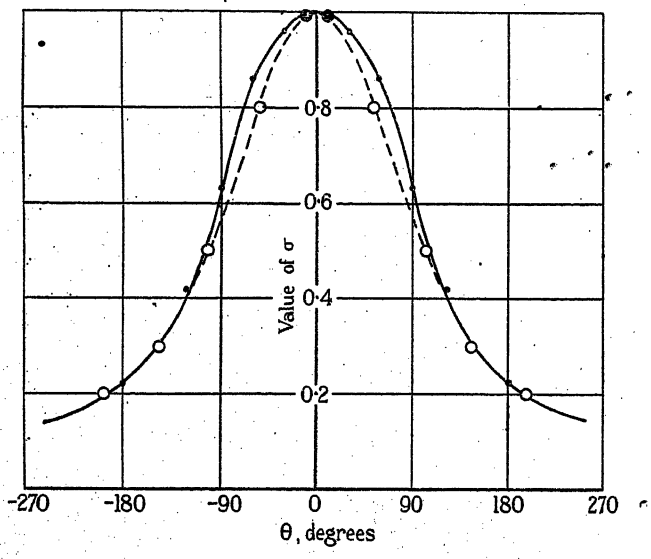


Fig. 12
● $\sigma = \sigma_0 s/l$
○ Observed

given of the relative potentials at corresponding points, taken on a $\frac{3}{4}$in mild-steel plate with 3in spacing of the electrodes and a current of 7 amp passing.

The significance of the agreement between the two curves is that even up to $\frac{3}{4}$in mild steel the form of the current field is not greatly different from that in thin plates of the same material, but it has shrunk towards the electrode axis; in a copper plate of this thickness the effect is more marked.

The lines of flow between points on a surface unlimited in depth and area may be regarded as having a resistance twice that between small spheres in a conducting medium. Jeans[7] has shown that the resistance between two spheres of radius a spaced a distance c between their centres is given by

$$R_1 = \frac{\rho}{2\pi}\left(\frac{1}{a} - \frac{1}{c}\right)$$

In the two-dimensional case

$$R_2 = \frac{\rho}{2\pi} \log \left(\frac{c}{a}\right)^2$$

The ratio $$k = \frac{2R_1}{R_2} = \frac{c-a}{2ac \log (c/a)^2}$$

Table 5 gives the value of k corresponding to specific values of a and c.

Table 5

a	c	k	$1/k$
in	in		
0·1	0·3	1·54	0·65
0·1	0·5	1·10	0·91
0·1	1·0	0·98	1·02
0·1	3·0	0·74	1·35
0·1	6·0	0·60	1·66

When the spacing is about 1 in there is little difference between the distribution in a thin, flat plate and that in a solid surface. The equations in the solid case have been given by Jeans.[8] The equation

$$\frac{x+c}{r_1} - \frac{x-c}{r_2} = \text{constant}$$

with the notation of Fig. 1 gives the lines of force between oppositely charged points in space. The distribution may be compared with that between charged lines as given in Sections 2.1 and 2.2.

Measurements made on a series of mild-steel plates enable an estimate to be formed of the change of shape of the field as the thickness is increased. The results of such measurements are given in Fig. 13. The curves show that when, as in the case of the B curves, the current is adjusted so that the potential difference between the exploring electrodes is kept constant as the thickness under test is increased, the currents are proportional to the thickness up to thicknesses of $\frac{3}{4}$ in. The distribution of current is then the same as in thin plates with boundaries at a great distance from the electrodes. Above this thickness a greater proportion of the current is gathered under the line joining the electrodes; and the working potential-drop along that line is reached with a relatively lower current. When the curves B reach a steady maximum value, as they may do when the electrode spacing is small or the potential applied is low, it means that the distribution of current between and around the electrodes is in effect the same as in a surface of infinite thickness. The resistance has then reached a steady value.

The curves A give the potential drop when the current is set to have the same value in each case. The ordinates of the B curves, hyperbolas up to $\frac{3}{4}$ in, are the inverse of those of the A curves. The number against each curve is the galvanometer deflection indicating the potential difference.

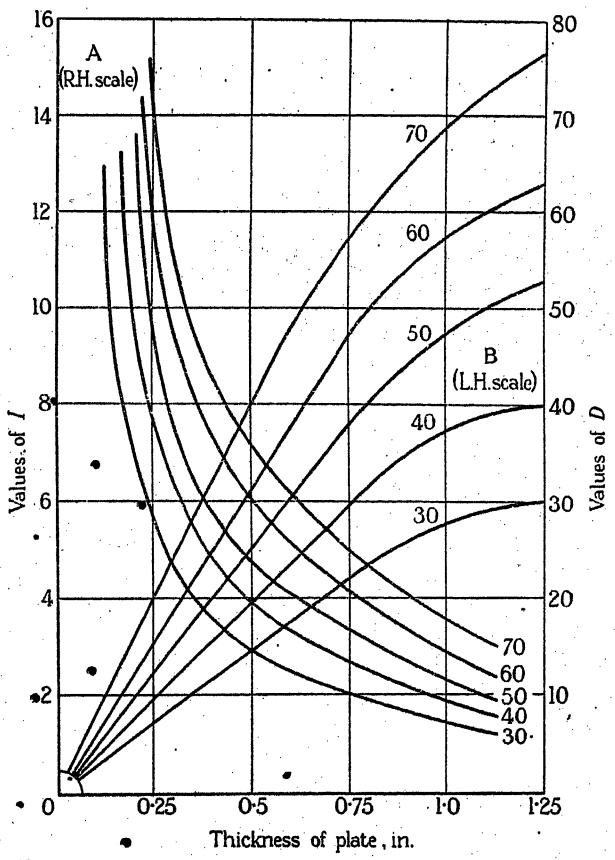


Fig. 13.—Results of measurements made on a series of mild-steel plates.

(13) THE INFLUENCE OF WIDTH OF SPECIMEN

In the application of the electrical method of measuring thickness it has frequently been found necessary to deal with surfaces which are bounded either by an edge parallel to the line of the electrodes or by ribs. In the latter case it is necessary to have for comparison a surface of known thickness and of the shape to be tested. Examples of the influence of edges have been given in the previous paper,[1] but some idea of the extent of the edge effect may be gathered from the simple case of a long strip with parallel edges, and with the electrodes placed on the median line. When the spacing s of the contacts is equal to or less than half the transverse breadth of the plate the flow between them is nearly the same as that in an infinitely wide surface. Taking as a close approximation to the transverse drop of potential, or of current density σ, the empirical expression $\sigma = \sigma_0/(1+x^2)$, where x is the distance from the axis of contacts and σ_0 the current density on that line when the plate has a breadth greater than $2s$, the effect of reducing the width (keeping the total current constant) is to raise the current density so that $\int \sigma dx$ is constant.

The area is given by $$2\int_0^\infty \sigma_0 \frac{dx}{1+x^2} = \pi\sigma_0$$

This is found to be, within a few per cent, the area of the curve on a specimen in which $b = 2s$. The area for any other breadth is given by $b = 2\sigma_b$ arc tan $b/2$, where σ_b is the maximum current density along the axis. When this area is to be constant

$$2\sigma_b \text{ arc tan } \frac{b}{2} = \pi\sigma_0$$

and $$\sigma_b = \frac{\pi}{2}\sigma_0 / \text{arc tan } \frac{b}{2}$$

Table 6

b	10	9	8	7	6	5	4	3
$D[=2\sigma_b/(\pi\sigma_0)]$	1	1·1	1·25	1·41	1·66	2·0	2·5	3·4

Taking 10 as an index figure for the breadth $b = 2s$, this gives the values shown in Table 6.

The value of D indicates the ratio in which the potential difference between the exploring points increases when the width of the specimen is reduced. The maximum current density is inversely proportional to the breadth. On the other hand, if the potential drop is kept constant the current necessary to produce it is represented by a straight line through the origin, corresponding near that point to the effect of contacts made on the edge of a very thin strip of unit depth, such as a clock spring. The figures show how quickly a reduction in the width of the specimen below the value $b = 2s$ begins to have effect, so that in practice measurements of thickness on narrow surfaces, whether free or bounded by ribs, can only be made by a comparison with similar surfaces of known thickness and of the same metal.

(14) THE THICKNESS OF TUBES

Curvature of surfaces such as those of tubes has little influence on the thickness measurements when, as in this method, the current is unidirectional. Interesting effects are found when the current is alternating, of which an account will be given elsewhere. Trial has shown that when the spacing of the current contacts along the surface of a tube of any metal parallel to its axis is not greater than 1·5 diameters the thickness measured in this way is very nearly the same as on a flat plate of the same metal and thickness. This has been found to hold for duralumin tubes 3 in diameter and $\frac{1}{2}$ in thick and for thinner steel tubes from 1 in to 4 in diameter. It would appear that the spread of the current is so little affected by the paths on either side of the contacts line meeting at the back of the tube that the potential drop is the same as that in a plate, within the limits of observation. A tube can in general be regarded as a flat strip the breadth of which is π times the mean diameter of the tube.

When the section is excentric it is equivalent to a plate tapering from the contact line towards thin parallel edges. A method of dealing with excentric sections has been given in the previous paper.[9] It has been found that internal erosion by the flow of heated liquids has had the effect of thinning a tube so that the inner and outer boundaries are still circular.[10] In such a case the resistance between contacts parallel to the centre line of the tube depends on their orientation. If they are placed on the thickest part of the section the resistance is greater than it would have been if the section had had that uniform thickness. When the contacts are placed on the thinnest part of the tube, of paper thickness, the resistance is less than it would have been on a concentric tube of the same (paper) thickness. The result is that while the calibration line connecting the testing current for a given deflection or p.d. is with concentric tubes a straight line which passes through the origin, that with excentric tubes no longer does so.

If r_0 is the radius of the outside surface and r_1 that of the inner, and the maximum thickness is t_0, we have $r_0 - r_1 = t/2$, and at any angle θ from the max./min. axis $t = \frac{t_0}{2}(1 + \cos\theta)$. This gives an eye-shaped area with sharp edges, not one of lenticular shape. Its area is $2\pi r_0 t_0/2$, half the original area; and the axial resistance of the section as a whole is doubled. This is the extreme case, though burst tubes have been found to approach to it.

(15) TAPERING SECTIONS

The flow around a tube between contacts made at opposite ends of a diameter may occasionally be used to detect thinning. The resistance of an uncorroded tube per unit axial length is $\frac{\pi}{2}\frac{r\rho}{t}$, r being the mean radius and t the thickness. When the section is excentric and the contacts are made on the max./min. axis the two half-sections in parallel are tapered. The resistance is then that of a half lune, from the thickest part to the edge. If the maximum thickness is T that at a distance x from the thin end of a flat strip wedge, Fig. 14, is $t = Tx/a$, where a is its

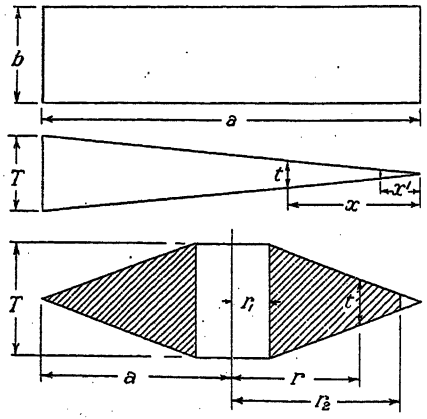


Fig. 14.—Tapering sections.

length. The element of resistance $dR = \rho dx/(bt)$, and so $R = \int \frac{\rho a dx}{bTx} = \frac{\rho a}{Tb}\log\frac{a}{x'}$, taken to a distance x' from the infinitely sharp edge at a. The gradient is given by

$$g = i\frac{dR}{dx} = \frac{\rho a}{Tb}\cdot\frac{i}{x}$$

The fall of the voltage gradient is hyperbolic.

It has been necessary occasionally to use rolling contacts with sharp edges, such as those of pipe cutters, keyed to shafts, the resistance of which is not negligible. Here

$$dR = \frac{\rho dr}{2\pi r t}, \text{ where } t = \frac{a - r}{a - r_1}T$$

The total resistance $R = \rho\frac{a - r_1}{2\pi T}\int_{r_1}^{r_2}\frac{dr}{r(a - r)}$

$$= \frac{\rho(a - r_1)}{2\pi T}\log\left(\frac{r_2}{r_1}\cdot\frac{a - r_1}{a - r_2}\right)$$

With a current flowing from the shaft to the contact surface at r_2 the total drop of potential is iR, and the gradient is given by

$$g = \frac{de}{dr} = \frac{i\rho(a - r_1)}{2\pi T}\cdot\frac{1}{r(a - r)}$$

When $$\frac{r_2}{r_1} = \frac{a - r_1}{a - r_2}$$

the potential gradient is the same, $i\rho/(2\pi T)$, at the inner and outer contacts and is least at the mean radius $a/2$.

(16) THE SIX-POINT METHOD

The usual position of the potential points in the "four points in line" method is a short distance within or without the current contacts. If now contact is made to the galvanometer from two other points in line with the first, the ratio of the new to the old deflections gives a measure of the thickness of the plate that is independent of the resistivity of the metal. This method has been found most useful in the measurement of large cast-iron cylinders and plates the composition of which is uncertain. The

electrical conductivity of cast iron varies with its composition much more than that of mild steel and, unless there is available a casting of known composition and thickness on which comparison readings may be made, the six-point method provides means of measurement the accuracy of which is shown in Fig. 15.

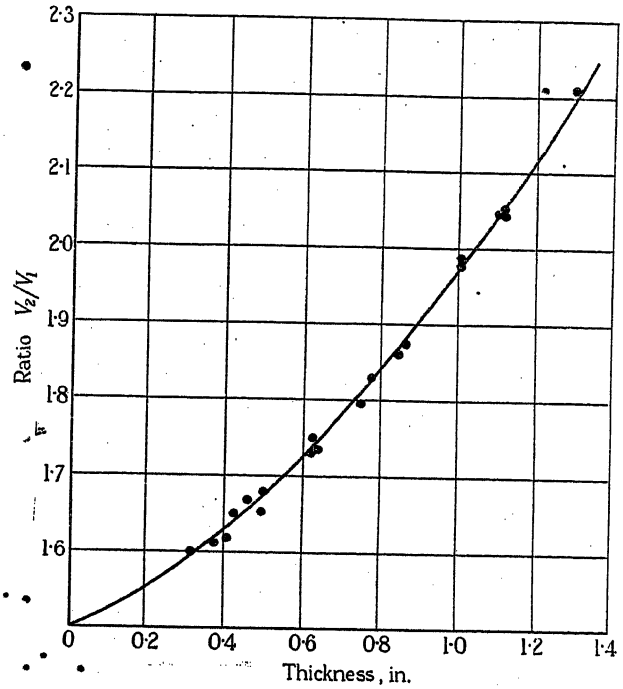


Fig. 15.—Accuracy of the "six points in line" method.

This "six points in line" method is based on the fact that the current density at a given point is, for the same total current, inversely proportional to the area of the current path; and since the conformation of this remains nearly the same for a wide range of thickness it is a function of the latter which depends mostly on the resistivity of the material. If this function does not change with the resistivity, the latter can be eliminated by taking p.d. readings at two additional points. The ratio of these two sets of p.d. readings gives a measure of the thickness which, once established by measurements on plates of any material, can be applied to measure that of others. This ratio has been found to be the same for plates of mild steel, cast iron, nickel, copper and duralumin. The ratio is greater when the plates are thick, for the current density is not uniform over the section of a thick plate. The current, and therefore the potential drop, along the surface is in effect shunted by the more remote parts of the metal. The curve of Fig. 15 is an example of the results obtained by this method on a set of carefully machined cast-iron plates and cylinders, the composition of which varied from 2·06 to 2·67 per cent graphitic carbon, 0·49 to 0·88 combined carbon, 1·27 to 1·88 silicon, 0·41 to 0·65 manganese, 0·44 to 1·35 phosphorus, 0·1 to 0·12 sulphur. In this case the six contacts were spaced at equal distances apart in line.

The equation to the mean line of the Figure is

$$\frac{V_2}{V_1} = a + bt + ct^2, \text{ where } a = 1{\cdot}5,\ b = 0{\cdot}225,\ c = 0{\cdot}25.$$

There are two possible ways of using the method. In one of them (Case 1) the two outer contacts are used to carry the current, and then V_2 in Fig. 16(*a*) is the potential difference between the

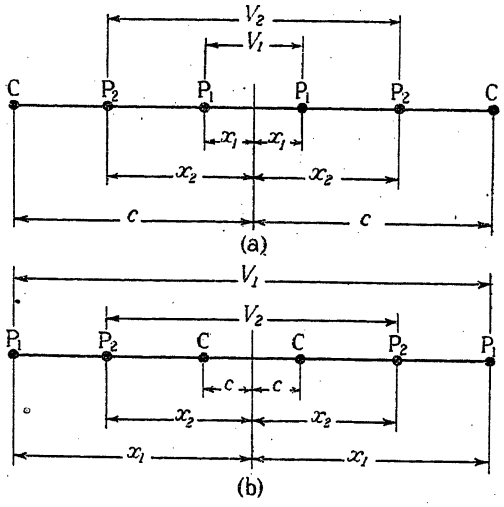


Fig. 16.—Diagrams illustrating the two ways of using the "six points in line" method.

contacts P_1 nearest to the electrodes, V_1 that between the inner contacts. Taking $2c$ as the spacing of the current contacts, and x as the distances of the potential contacts from the mid-position,

$$\frac{V_2}{V_1} = \frac{\rho I}{A_2}\cdot\frac{A_1}{\rho I}\cdot\frac{\log (c+x_2)/(c-x_2)}{\log (c+x_1)/(c-x_1)} = \frac{A_1}{A_2}\cdot\frac{\log 4}{\log 1{\cdot}5} = 3{\cdot}4\frac{A_1}{A_2}$$

Hence $3{\cdot}4\,.\,A_1/A_2 = a + bt + ct^2$, and is independent of the resistivity.

The ratio of the effective areas A_1, A_2 of the sections under the potential is in this arrangement a quadratic function of the thickness. The other way of using the method (Case 2) is as follows: When the two inner contacts carry the current, Fig. 16(*b*),

$$\frac{V_2}{V_1} = \frac{A_1}{A_2}\cdot\frac{\log (x_2+c)/(x_2-c)}{\log (x_1+c)/(x_1-c)}$$

and here $x_1 = 5c$, $x_2 = 3c$, $\frac{V_2}{V_1} = \frac{A_1}{A_2} \times 1{\cdot}7$, in which case $1{\cdot}7A_1/A_2 = a + bt + ct^2 = 1{\cdot}5 + 0{\cdot}225t + 0{\cdot}25t^2$. The areas are given by $A = 2\pi at$, where a is the radius of the equipotential circle and t the thickness of the plate. Thus the ratio $A_1/A_2 = a_1/a_2$ and

$$\frac{a_1}{a_2} = \frac{\text{cosech } V_1}{\text{cosech } V_2} = \frac{\sinh V_2}{\sinh V_1}$$

The curve of Fig. 15 cuts the vertical axis at a value of V_2/V_1 of 1·5. Thus to determine the ratio a_1/a_2, for thin plates, values of sinh V_2 and sinh V_1 are found from tables, subject to the condition that $V_2/V_1 = 1{\cdot}5$. For Case 1;

$$a_1/a_2 = 1{\cdot}5/3{\cdot}4, \text{ when } t = 0$$

and

$$\frac{\sinh V_2}{\sinh V_1} = 0{\cdot}44$$

From which

$$\frac{a_1}{a_2} = \frac{5{\cdot}09}{2{\cdot}25} = 2{\cdot}27$$

For Case 2, $a_1/a_2 = 1/(1{\cdot}7 \times 1{\cdot}5)$, since the magnitudes of the potentials V_2 and V_1, are reversed, the equipotential of smaller radius having the higher value of V. Here

$$\frac{\sinh V_2}{\sinh V_1} = 0{\cdot}88 \text{ and } \frac{a_1}{a_2} = \frac{8{\cdot}19}{3{\cdot}16} = 2{\cdot}58$$

Referring to (*a*), Fig. 16, the centres of the equipotentials through P_1 and P_2 for Case 1 can now be found, for $h^2 = a^2 + c^2$. From the Figure, $a_1 = h_1 - 0{\cdot}2c$, and

$$h_1^2 = (h_1 - 0{\cdot}2c)^2 + c^2$$

$h_1 = 2{\cdot}6c$, measured from the mid-point O.

Also
$$a_2 = h_2 - 0{\cdot}6c$$
$$h_2^2 = (h_2 - 0{\cdot}6c)^2 + c^2$$

and
$$h_2 = 1{\cdot}135c$$

For Case 2,

$$a_1 + h_1 = 5c, \quad h_1^2 = a_1^2 + c^2 \text{ and } h_1 = 2{\cdot}6c$$
$$a_2 + h_2 = 3c, \quad h_2^2 = a_2^2 + c^2 \text{ and } h_2 = (5/3)c$$

The displacement of the centres of the equipotential circles caused by the increased thickness of the plate can be found in this way by taking values of V_2/V_1 from Fig. 15 for any value of t, and proceeding as described above.

(17) FORMULAE DERIVED OR QUOTED

1. Equation of lines of flow between line electrodes,

$$x^2 + y^2 - 2cx \coth V + c^2 = 0$$

2. Equation of lines in a section of a three-dimensional field,

$$\frac{x+c}{r_1} - \frac{x-c}{r_2} = \text{constant}$$

3. Potential along lines in two-dimensional case,

$$V = 1/\log\left[\frac{r}{c} + \sqrt{\left(\frac{r}{c}\right)^2 + 1}\right] = \text{arc cosech } r/c$$

The gradient $g = \dfrac{dV}{dr} = \dfrac{-1}{r\left[\left(\frac{r}{c}\right)^2 + 1\right]^{\frac{1}{2}}}$

4. Resistance between electrodes of radius a spaced a distance s apart,

$$R = \frac{\rho}{2\pi} \log \left(\frac{s}{a}\right)^2$$

5. Resistance between hemispherical electrodes in a solid surface, $R = \dfrac{\rho}{\pi}\left(\dfrac{1}{a} - \dfrac{1}{c}\right)$, where a is radius and c spacing.

6. Circle in a uniform field, $R = \dfrac{\pi}{2}\rho$, $g = \dfrac{\rho I}{2a}$

7. Prolate ellipse in a uniform field,

$$R_p = \frac{\pi}{2} \cdot \frac{a}{b}\rho, \quad g = \frac{\rho I}{2b}, \quad V_{max} = \frac{\rho I a}{b}$$

Oblate ellipse,

$$R_0 = \frac{\pi}{2} \cdot \frac{b}{a}\rho, \quad g = \frac{\rho I}{2a}, \quad V = \frac{\rho I b}{a}$$

$$R_p/R_0 = a^2/b^2$$

8. Concentric cylinders, $R = \dfrac{\rho}{2\pi} \log \dfrac{b}{a}$, $g = \left.\dfrac{\rho I}{2\pi r}\right]_b^a$

Sector of a cylinder, $R = \dfrac{\rho}{\alpha} \log \dfrac{b}{\alpha}$, $g = \left.\dfrac{\rho I}{\alpha r}\right]_b^a$

9. Square between corners,

$$R \simeq \frac{2\rho}{\pi} \log \frac{h}{a\sqrt{2}}, \quad g = \frac{2\rho I}{\pi r}$$

Rhombus, $R \simeq \dfrac{\rho}{\alpha} \log \dfrac{h}{a\sqrt{2}}$, $g = \dfrac{\rho I}{\alpha r}$

10. Narrow lenticular element, from α' to $-\alpha'$,

$$R = \rho\left(\alpha' + \cot\alpha \log \frac{\tan\alpha/2 + \tan\alpha'/2}{\tan\alpha/2 - \tan\alpha'/2}\right)$$

11. Wide lenticular element,

$$R \simeq \frac{\rho}{\alpha^2\alpha'}\left\{1 + 2\left[1 - \left(\frac{\alpha'}{\alpha}\right)^2\right]\cos\alpha\right\} - \frac{\rho}{4\alpha^3} \log \left(\frac{\alpha + \alpha'}{\alpha - \alpha'}\right)^2$$

12. Circle along a diameter, $R = \dfrac{2\rho}{\pi} \log \dfrac{d}{a}$

13. Ellipse along the major axis, $R = \dfrac{2\rho}{\pi} \log \dfrac{2a^2}{bc}$

Ellipse along the minor axis, $R = \dfrac{2\rho}{\pi} \log \dfrac{2b^2}{ac}$

14. Narrow lune,

$$R = \rho \frac{r_1 + r_2}{r_2 - r_1} \cdot \cot\alpha \cdot \log \frac{\tan\alpha/2 + \tan\alpha'/2}{\tan\alpha/2 - \tan\alpha'/2}$$

15. Transverse current densities,

$$\sigma = \sigma_0/(1 + x^2), \quad \sigma_b = \sigma_0 \frac{\pi}{2}/\left(\text{arc tan}\frac{b}{2}\right)$$

16. A tube with axial contacts presents the same problem as a plate with the width of the tube circumference.

17. Flat wedge, $R = \dfrac{\rho a}{bT} \log a/x'$

18. Tapered disc, $R = \dfrac{\rho(a - r_1)}{2\pi T} \log \left(\dfrac{r_2}{r_1} \cdot \dfrac{a - r_1}{a - r_2}\right)$

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(7) J. H. JEANS: *ibid.*, p. 352, § 387, III.

(8) J. H. JEANS: *ibid.*, p. 50, § 63.

(9) See Reference (1), p. 375, Fig. 19.

(10) See Reference (1), p. 373, Fig. 16.

BONDED DEPOSITS ON ECONOMIZER HEATING SURFACES

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SUMMARY

The problem of boiler plant availability in power stations has become so prominent that a better understanding is essential of the causes of the fouling of heating surfaces by deposits from the products of combustion.

Earlier theories based on fused ash particles, sodium sulphate bond or high dew-points have not satisfactorily accounted for various well-established facts of observation. The latter include the existence of a period of apparent immunity from deposits in a new boiler plant, the characteristic behaviour of the dust from pulverized fuel firing and the peculiar scale-like form of certain hard deposits occurring on economizer and boiler tubes.

The authors, restricting their observations largely to economizers, have found that hard bonded deposits result from certain chemical reactions between flue dust and sulphuric acid. The type of reaction depends on the temperature of the metal parts associated with the deposits.

A clear understanding of the reactions involved in the formation of these deposits indicates methods for removing them.

The authors offer practical suggestions for the prevention of hard bonded scale formation in economizers. Various types of coal ash are discussed, and characteristics favouring bonded deposit formation are pointed out. The influence of the authors' proposals on plant design is considered.

(1) INTRODUCTION

In his Inaugural Address to The Institution in October, 1939, Sir Johnstone Wright drew attention to the influence of boiler availability on capital and operating costs. He said: "There is a wide gap between the average availability of turbo-alternators and boilers, and every effort should be made to ensure better boiler availability, and thus avoid capital locked up in the boiler house lying idle for long periods of the year."

For many years users and plant manufacturers have been conscious of the various aspects of the boiler availability problem, but the progress made in solving it has on the whole been disappointing. Partial solutions of particular difficulties have occasionally been achieved, but the authors doubt whether it can be claimed that any one of the more serious general problems involved in "keeping the boiler on the line" has been finally and completely solved. This is more particularly true in the case of central power stations.

One of the chief groups of "availability problems" is that which relates to deposits on the gas-swept surfaces of economizers and air-heaters.

A sufficient accumulation of such deposits will lower the steam output of the whole unit until it is necessary to shut down for cleaning.

The deposit not only reduces heat transference in an important auxiliary; it causes such an increase in draught loss that the fan equipment cannot cope with it.

The load which the boiler can carry falls off rapidly, and a point is reached when the unit has to be cleaned down to enable it to function again at its full output and efficiency.

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In most industrial plants using boilers of the Lancashire type, the economizer deposits are a conglomeration of soot, ash and grit, impregnated with dilute sulphuric acid. Such deposits are generally loose, and if the feed inlet temperature is high enough to avoid moisture condensation on the economizer tubes it is easily removed. In the experience of many years the authors have never encountered a true, hard, bonded deposit in the normal Lancashire boiler-cum-economizer steam plant. As a general rule in such plants, the economizer deposit problem, where it exists at all, is adequately solved by the familiar mechanical scraping equipment.

There are cases where the deposit contains a proportion of tarry matter. Where this constituent is in excess, the scrapers may fail to function properly, and the solution to the problem then lies in attending to the combustion conditions.

With water-tube boilers in industrial, as distinct from power station, practice, much the same applies. The deposits are dry, loose and often powdery. Mechanical scrapers on vertical economizer tubes give results which are usually completely satisfactory. The introduction of the "extended surface" or gilled-tube economizer posed the problem afresh. No simple form of mechanical scraper could be devised for cleaning a gilled tube, and the soot blower, using steam, compressed air and sometimes water, was employed to effect intermittent removal of deposits.

The results were various in the extreme. In many cases the combination of gilled tube and soot blower was very satisfactory: in others the performance was far from good. Various types of blowers were applied to what had become fairly standard forms and arrangements of gilled tubes, and again the results varied.

There was much success, but there always remained a residuum of "difficult cases." In some of these the troubles were traced to poor combustion; in others cold feed was the cause. Ultimately greater emphasis came to be placed, first on economizer arrangement, and secondly on tube form. It was found that certain systems of arrangement—in particular that of dividing an economizer into shallow tiers or banks—had pronounced advantages, in that the heating surface related to a particular blower could be kept within the effective range of the latter, and in that case of access for inspection and maintenance work was increased.

It was found, or at any rate claimed, that certain tube forms collected less dust than others. It is in this direction that the greatest progress has probably been made. Although the last word in matters of tube form and economizer arrangement has by no means been said, the gilled economizer designs which have been developed in the last four or five years provide a reasonably satisfactory answer to the deposit problem under "industrial" conditions.

(1.1) Bonded Deposits

It is well known that the type of deposit which gives most trouble, whether in boilers, economizers or air-heaters, is the hard, scale-like, *bonded* substance on which soot blowers of whatever type have little effect.

It is to this kind of deposit, occurring mostly in power station plants, that the authors have in the past few years directed their

attention, and in connection with which they now offer their conclusions.

These constitute a complete theory of the formation of bonded deposits on economizers under "power-station" conditions. Although there is still much work to be done on many issues which have been raised during the course of the investigations, the authors believe that the present findings indicate methods of achieving a pronounced increase in boiler availability.

They have in recent years, as a part of their normal duties, investigated many specific cases of deposit difficulties, and have been able to collect many samples of deposit. It was not, however, until they felt that their collection was sufficiently representative, that they were able to make a systematic attack on the problem.

(1.2) Existing Theories

The first task was to review the work already done by other investigators on this subject of bonded deposits, and to judge their theories by some criteria based on the authors' own experience.

There are three principal groups of theories, which may be classified in the following way:—

(*a*) *The "Fused Ash" Theory.*

This theory holds that the coal ash, in the form of flying incandescent plastic particles, impinges on the surfaces of economizer tubes, provides a temporarily "sticky" base for the adherence of dust and grit, and forms the "bond" which quickly solidifies and hardens.

(*b*) *The "Sodium Salt" Theory.*

Coal ash contains sodium salts, which combine with the sulphuric acid in the gases and form sodium sulphate. This comparatively infusible salt "condenses" on the economizer tubes and forms, with the grit, dust and ash, the hard-bonded scale.

(*c*) *The "Dew-point" Theory.*

If an economizer tube surface is below the "dew-point" of the gases, moisture will condense and will trap and hold small dust particles. If the gases contain sufficient sulphur trioxide, "dew-points" may occur at high temperatures.

(1.3) The Test Criteria

There are certain well-established facts of observation which any completely satisfying theory must adequately explain. The authors distinguish three such facts, and apply them as criteria to the existing theories.

"A." *Period of Immunity.*

It is known that an economizer will frequently work for a period of 6–12 months, and even longer, and will apparently keep perfectly clean. Then a thin, hard scale of no more than eggshell thickness appears. Thereafter the growth of deposit becomes rapid. Whatever the tube form or economizer arrangement, and whatever the soot-blowing system, the accumulation of bonded deposit appears inevitable and proceeds with acceleration.

"B." *Bonded Deposits associated with Stoker Firing.*

It is known that hard, bonded scales occur only on economizers installed with stoker-fired boilers. In none of the numerous pulverized-coal-fired plants examined has a true bonded deposit been encountered.

"C." *Overlapping Stalagmitic Scale Formation.*

The rough overlapping scale structure, growing in the direction opposed to the gas flow, is a definite characteristic of bonded scale.

In the opinion of the authors, none of the three principal groups of theories satisfactorily explains these three observed facts.

(1.4) The "Fused Ash" Theory

Coal ash fuses at approximately 2 000° F. Such "fly ash," while still in the incandescent state, may reasonably be expected to accumulate, solidify and bond on surfaces very close to the combustion chamber. This simple building-up is probably a cause of "bird-nesting," and produces a structure which is cellular in character, and more or less of the "cinders and clinker" type. But this is not the kind of deposit which forms on the economizer tubes. Applying the three criteria, the following results emerge:

"A." If the "fused ash" theory held, growth on the economizer would be gradual and continuous from the time the plant went into commission. There would be no lengthy period of immunity.

"B." As most of the ash in pulverized-coal-fired plants passes forward through the boiler, and as incandescent particles are the very essence of the combustion process, it would be reasonable to expect economizer deposits to build up very quickly in such plants. It is, however, well known that, though the ash particles are in abundance, bonded deposits in pulverized-coal-fired plants are practically non-existent.

"C." The stalagmite scales of a bonded deposit face the gas flow, and form excellent cavity traps for fused or partially fused particles. On the "fused ash" theory one would expect that this fact would *prevent* rather than *cause* stalagmitic growth. The deposit ought to be a fairly uniform agglomeration of flattened particles similar in structure to those obtained in the metal-spraying processes. The particles have not, in fact, these characteristics.

The "fused ash" theory was put forward by Johnstone* in America in 1931. He explained that fused iron sulphide (which, incidentally, melts at 2 133° F) was the cause of scaling. Johnstone made this suggestion in spite of the fact that he never recorded more than 0·148% of sulphide sulphur in fly ash.

The theory was supported by Prantner† as late as 1939, in connection with the problem of deposit removal.

Their examination of the "fused ash" theory led the authors to investigate not only the deposits on economizer tubes but also those accumulations which occurred on surfaces near to, but not part of, the economizer. It was observed that whilst the deposit on the economizer surface would be a bonded scale, that on the neighbouring casing ledges, on support plates and steelwork, on soot-blower parts and on firebrick linings, was almost invariably a loose dust and never bonded.

In the examination of these dusts they were graded in the usual way and then subjected to air elutriation tests. It was found that two different air velocities were required for the complete removal of the particles from each sieve. This was an unexpected and rather surprising result, but the authors consider that it may have an important significance in boiler and economizer design.

The first separation, at lower air velocity, carried forward the irregularly shaped particles (Fig. 1) and left behind a quantity of particles which were almost completely spherical (Fig. 2).

Round or spheroidal particles have always been associated with the dust from pulverized-coal firing, but these differ from the spheroids from stoker firing in that the latter are *solid*, whilst the former are *hollow*. Specific gravity tests make this

* "The Corrosion of Power Plant Equipment by Flue Gases," *University of Illinois Bulletin*, 1931, 28, No. 41.

† "On the formation of deposits on the gas side of heating surface—Reduction and Removal," *Die Waerme*, 15th April, 1939.



Fig. 1.—Flue dust. Irregular grains. 60 mesh × 25.

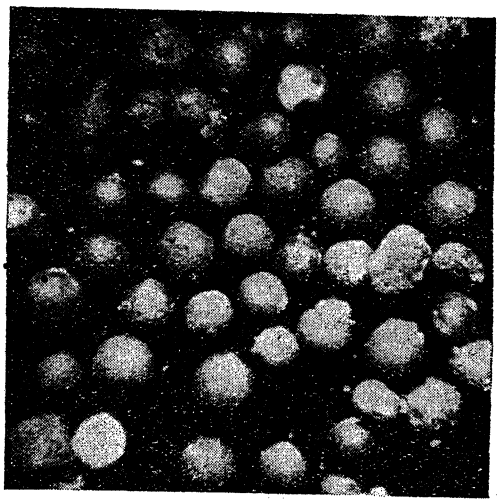


Fig. 2.—Flue dust. Round grains. 60 mesh × 25.

ifference clear. The figures are averages of a number of amples:—

	Sp. gr.
Dust from pulverized fuel	1·245
Dust from stoker firing (round)	2·356
Dust from stoker firing (irregular)	1·900

It is imagined that the irregular particles would escape from ıe grate in a comparatively cool condition. The spheroids, on ıe other hand, are probably burning particles carried forward ı the gas stream, the heat of combustion fusing the associated sh, and surface tension producing the spheroidal shape.

The important point in relation to the "fused ash" theory is ıis: since the rounded particles are spheroids, they must have ɔlidified before they reached the surface from which they were ollected. They must, therefore, have lost any plastic and sticky" properties whilst still in the gas stream.

On heating these spheroids, they were found to be quite solid ıd hard at 1 800° F. The authors therefore felt bound to reject ıe "fused ash" theory, and inclined to the view that though ɔnded scales must be formed from loose dust, the bonding kes place at some time after the deposition on metal surfaces.

(1.5) "The Sodium Salt" Theory

When careful examination is made of the work of investigators ho have given special attention to deposit formation, remarkable variations are encountered. Paul,* in 1919, gave a number of analyses of external deposits. He included such figures as 65·10% and 84·32% of sodium sulphate. On the other hand Johnstone,† in 1931 also gave numerous analyses, but he does not include figures for sodium salts. In a note, he states that in general these were not determined, but could be taken as being equivalent to approximately 2% to 7% Na_2O.

Johnstone was a careful experimenter; his research was a valuable contribution and in many ways must be regarded as a standard work on the subject. The care with which data were collected, analysed and presented, and the analytical ability displayed in the research, compel us to the conclusion that had there been any large quantity of sodium salts in the various deposits they would have been noted and recorded in the analyses. That the discrepancy cannot be due to a peculiarity of American coals is evidenced by the report of other workers who have claimed to find large quantities of sodium compounds in coal ash.

Later writers have tended to follow Paul rather than Johnstone. Since Paul published his results, many textbooks and papers appearing in this country have accepted his theory that sodium salts are the foundation and basis of bonded deposits, and this theory is accordingly examined by applying the three criteria.

The authors have investigated many economizer deposits. The analysis for sodium is difficult, and quantitative estimation is long and tedious. The results confirm the view taken by Johnstone. The majority of deposits contained only 1 to 2% of sodium sulphate. There was one special case where the coal burnt had been collected from the seashore. The coal sample contained 1·15% of sodium chloride, and the economizer deposit 38% of sodium chloride. The total sulphur in the deposit, however, was only 1·18%, so that even this special case could hardly be taken to confirm the results of Paul and the workers who follow him. The authors' results and other published evidence show that many deposits undoubtedly contain little sodium sulphate. On the other hand, there may be deposits, especially those occurring on boiler and superheater tubes, which contain a higher proportion.

Applying the criteria:—

"A." The "sodium salt" theory offers no explanation of the period of immunity. Deposits should build up, at a regular rate, from the start.

"B." The "sodium salt" theory does not explain why the dust from pulverized-coal firing does not form bonded deposits.

"C." The theory does not explain the stalagmitic structure of the deposits.

The authors accordingly felt compelled to reject the "sodium salt" theory as applied to economizers.

(1.6) Dew-point Theories

Examination of a large number of power station economizers under operating conditions, after various periods of service, revealed that if a surface—metallic or non-metallic—is at all times approximately at the same temperature as the local gas stream, the deposits which collect are not hard, do not bond, and may easily be removed by direct blowing with steam jets.

Thus, a steel supporting bar will hold loose dust only, whilst the adjacent economizer tubes will collect a bonded deposit. Such portions of the soot-blowing equipment as obey this temperature rule remain immune from bonded deposits. Other portions, cooled by a constant air-infiltration, have been found to collect a hard scale similar to that on the economizer tubes (Fig. 3).

It is not surprising, therefore, that such phenomena should have directed the thoughts of investigators to the subject of

* "Boiler Chemistry and Feed Water Supplies," pp. 205, 206.
† *Loc. cit.*, 1931, 28, pp. 49, 50.



Fig. 3.—Portion of hard scale (× 1½) from an economizer tube, viewed from above. The direction of gas flow was from left to right.

dew-points. It has long been known that where economizers are fed with water at low temperatures—below 100° F—moisture from the flue gases condenses on the tubes containing the coldest water, leading to a more or less rapid direct attack on the tube metal by the sulphur acids thus formed.

Much helpful work has been done on this subject, more especially on the elevation of the dew-point in relation to the sulphur compounds in the flue gases. Johnstone,* in America, and Taylor,† in England, have made important contributions, and have shown that dew-points of flue gases can vary up to 400° F and higher, depending on the concentration of sulphur trioxide and moisture present.

Sulphur trioxide has a marked influence on the dew-point. Taylor showed that with 5·1% water vapour the dew-point is 92° F, but if only 0·2% of H_2SO_4 is introduced into the gases the dew-point is raised to 405° F.

Consideration of these facts, in relation to the "dew-point" theory, raised the question: If bonded deposits occur on economizer tubes containing water between 250° F and 400° F, do the gases always contain sufficient sulphur trioxide for this temperature range to be below the dew-point?

The authors imagine the answer to this question to be in the negative. The amount of sulphur trioxide in boiler flue gases is very small indeed.

(1.7) Provenance of the Sulphur Compounds

Johnstone‡ suggests that most of the sulphur trioxide in the gases might come from sulphates in the coal. He gives the following example of two coals:—

	A	B
Total sulphur	2·26%	4·24%
This sulphur occurs as follows:—		
Sulphate sulphur	0·08	0·26
Pyrites sulphur	1·76	1·40
Organic sulphur	0·42	2·58

Pyrites and organic sulphur form sulphur dioxide. The sulphate sulphur forms some trioxide, but reducing agents probably convert a portion of this to the dioxide. Calcium sulphate in coal ash, for example, decomposes slightly at 400° C and completely above 960° C.§ At 870° C it begins to react with silica, and forms some sulphur trioxide. Similarly, iron sulphate in ash begins to decompose at 400° C.‖

In the two examples given by Johnstone, the gas analyses showed the following percentages (by volume):—

	A	B
Sulphur dioxide	0·133	0·357
Sulphur trioxide	0·002	0·010

The sulphate sulphur was not wholly converted to the trioxide. The actual trioxide percentage of the total possible trioxide was given as: A, 41%; B, 43%.

British coals, taken by and large, have an average sulphur content of about 1%. It is worthy of note that remarkably little information is available regarding the amount of sulphate sulphur present in our own coals.

The conclusion drawn from the above is that the flue gases contain very little sulphur trioxide, and that most of the sulphur is present as the dioxide. Small as this trace of trioxide appears to be, its presence, as will be shown later, is of the greatest importance.

Again the theory is examined in the light of the three criteria:—

"A." The "dew-point" theory does not explain the long period of immunity *and* the subsequent rapid acceleration of deposit accumulation. Here again, on this theory, deposits should form from the outset, and, as the surface temperature rises with thickening layers of deposit, the rate of condensation of trioxide should diminish and presumably the rate of deposit accumulation should become less. Observed facts do not confirm this.

"B." The "dew-point" theory does not fully explain the comparative immunity of pulverized-coal-fired plants from bonded deposits.

"C." The "dew-point" theory does not appear to offer any explanation of stalagmitic growth. Indeed, as has been said above, the higher temperature of the scale surface should, on this theory, tend to retard condensation. Observation shows that the stalagmitic structure is related to an acceleration in the deposition process.

The authors are compelled to reject the theory on the grounds that it does not satisfactorily explain the facts. There will, however, be occasion to refer to certain important aspects of dew-point phenomena, and the authors acknowledge their indebtedness to the work of Johnstone and Taylor in this connection.

(2) THE PRESENT INVESTIGATION

It will be clear that although earlier research has brought out many interesting and useful points, the actual processes involved in the formation of hard bonded scale have not yet been explained in a satisfying manner. The authors therefore turned to a renewed examination of the very large number of bonded-deposit samples they had collected, and began by ascertaining what characteristics, if any, were common to all.

In what has gone before, a distinction has been implied between "industrial" and "power station" conditions, and it may be as well to inquire at this point in what important respect these conditions differ, since, as has already been said, bonded deposits on economizers appear to form exclusively under what have been termed "power station" conditions.

From the economizer standpoint there emerge two distinguishing characteristics, of which one seems to be more important than the other.

The first is the water temperature range. In industry this range in economizers lies almost entirely between the temperatures of 100° F and 350° F. In power stations, more particularly in recent years, the range is much higher. A power station economizer is seldom fed with water below 250° F; inlet feed temperatures in excess of 400° F are not unknown. The outlet feed temperature is often above 450° F. Power stations, therefore, are usually concerned with a range between 250° F and 450° F.

The reasons for this difference in practice are well known and need not be discussed here.

The second point is that combustion is perhaps a little more complete in a power station plant than in an industrial plant. The percentage of combustible in the deposit from a power station economizer is usually negligible. Where a deposit accu-

* "An Electrical Method for the Determination of the Dew Point of Flue Gases," *loc. cit.*, 1929, 27, No. 13.

† "Relation between Dew Point and the Concentration of Sulphuric Acid in Flue Gases," *Journal of the Institute of Fuel*, 1942, 16, p. 25.

‡ *Loc. cit.*, 1929, 27, pp. 16, 17.

§ J. R. PARTINGTON: "A Textbook of Inorganic Chemistry" (4th ed., 1933).

‖ H. F. JOHNSTONE: *loc. cit.*, 1929, 27, No. 13.

mulates in an industrial economizer, a fairly high percentage of combustible matter is often present in the deposit.

It will, of course, be well understood that this approximate classification is not clear-cut. There are "industrial" plants whose steam and generating equipment is to all intents and purposes that of a power station. There are smaller "power stations" which partake of the characteristics of industrial plant. For the purpose of the discussion which follows, the classification will not be misunderstood.

(2.1) Deposit Examination

Two facts emerged at an early stage in the investigation:—

(*a*) Coal ash consists mainly of compounds of silica, alumina, iron oxide, lime and magnesia in various proportions.

(*b*) The authors found that sulphuric acid, and alumina in some form or other, were constituents common to *all* deposits; they found also that aluminium sulphate is a constituent common to all hard bonded deposits formed on economizers in the "power station" range, i.e. containing feed water between 250° F and 450° F. Hard bonded deposits from economizer tubes have been analysed, and also the loose dust deposits from nearby ledges. The results given in the Table are typical.

Table

	Station X		Station Y	
	Hard deposit	Loose dust	Hard deposit	Loose dust
Moisture	2·10	0·09	2·35	1·22
Ash	82·80	57·50	68·60	78·90
Insoluble in water ..	82·18	98·00	58·54	82·89
Soluble in water ..	17·82	2·00	41·46	17·11
Total S as H_2SO_4 ..	8·42	0·84	38·98	13·82
Soluble Portion				
Ferric sulphate ..	0·28	Nil	3·50	5·65
Aluminium sulphate	8·36	Nil	12·00	0·0
Calcium sulphate ..	1·70	0·73	2·99	4·74
Sulphuric acid ..	5·88	Nil	21·60	5·44
Note.—Aluminium sulphate was hydrated in Station X analyses and dehydrated in Station Y analyses.				
Insoluble Portion				
Iron oxide	0·64	0·04	15·26	10·74
Aluminium oxide ..	37·97	17·88	13·45	30·36
Silica	16·40	17·44	12·95	28·90
Calcium sulphate ..	Nil	0·44	Nil	5·76
Calcium oxide ..	Nil	2·12	Nil	Nil
Water Temperatures				
Station X			*Station Y*	
Inlet 275° F; outlet 356° F.			Inlet 320° F; outlet 392° F.	

These figures are significant. It will be seen that the total sulphur in the hard deposit is much greater than that in the loose dust. It will also be observed that even though the loose dust may contain an appreciable amount of sulphur, it shows no tendency to cake or bond. The dust must clearly lack some essential factor which is in some way associated with the economizer tube.

The nature of the metal does not explain the difference. Cast-iron gilled sleeves on economizer tubes will collect a hard deposit, whilst adjacent steel sootblower tubes do not. Bare steel economizer tubes will also accumulate a bonded scale; adjacent cast-iron supports do not.

Observations at a number of installations shows that the hard deposit forms only if:

(*a*) The surface on which the deposit settles is metallic.

(*b*) The surface on which the deposit settles is always at a temperature lower than that of the dust-laden gases which pass over it.

Item (*b*) has led many investigators to the conclusion that deposit formation is therefore a dew-point phenomenon. Dew-point *alone*, however, cannot be the explanation, since bonded deposits form when the metal surfaces are at a temperature much above the gas dew-point, in spite of the sulphur trioxide content.

(2.2) The Bond

The next step was to consider the various analyses to discover the cementing agent or bond. The constituent which occurs in quantity in all hard deposits is aluminium sulphate. The characteristics of this substance, in the pure state, were therefore examined. A number of interesting features were observed.

When aluminium sulphate is *quickly* heated to above 420° F it swells up and passes through a stage which can best be described as highly glutinous. It finally becomes a hard, dry salt. The swelling stage occurs during the loss of combined water, the final product being the dehydrated aluminium sulphate. On further heating to above 1 400° F, the sulphate decomposes, loses its sulphur trioxide, and is converted back into aluminium oxide.

It was realized that if the formation of hydrated aluminium sulphate [$Al_2(SO_4)_3 . 18H_2O$] took place in a deposit, and if at some subsequent stage it was thrown out of solution in an atmosphere above 420° F, it would immediately pass through the "glutinous" condition and present a surface to which further dust could and would adhere, and finally result in a bonded deposit having the familiar characteristics.

These considerations appeared to indicate a promising line of research, more especially as the reactions involved in the formation of aluminium sulphate in the deposits seem to have received little attention.

Johnstone says:* "a large part of the sulphur present in the deposits exists as iron and aluminium sulphate. These are undoubtedly formed from the fly ash itself, and are not the result of any action of sulphuric acid on the ash."

The authors find this statement unsatisfactory. Most authorities agree that in the coal ash the aluminium occurs as aluminium silicate. To form the sulphate, the necessary sulphate radical must be added by the direct action of either sulphur trioxide or sulphuric acid. But the gases contain very little trioxide, and any such reaction occurring during the passage of the dust from the combustion chamber to the economizer must be very limited.

If, however, the minute particles of alumina were to lodge on the tubes bearing an external film of hot sulphuric acid, the conditions would be propitious for the formation of aluminium sulphate; time and opportunity would be favourable.

In explanation of the little attention which has been given to this aspect of deposit constitution, it is suggested that there seems to be some uncertainty about the solubility of alumina or aluminium silicate in sulphuric acid. Most chemistry textbooks state that $Al_2O_3 . 3H_2O$ is soluble in sulphuric acid; that $Al_2O_3 . 2H_2O$ is fairly soluble; and that Al_2O_3 is comparatively insoluble. It is also suggested that when Al_2O_3 is heated above 800° C a change in allotropic form takes place, the specific gravity increases, and the alumina becomes totally insoluble. Bearing in mind that fly ash comes from a high-temperature zone in the boiler furnace, it is not surprising, if the textbook statements are accepted without further inquiry, that the possibility of the existence of soluble alumina compounds in fly ash has not received much attention.

* *Loc. cit.*, 1931, 28, p. 52.

Partington* gives the following:—

$Al_2O_3 . 3H_2O$ heated to 80° C becomes $Al_2O_3 . 2H_2O$.
$Al_2O_3 . 2H_2O$ heated to 235° C becomes $Al_2O_3 . H_2O$.
$Al_2O_3 . H_2O$ heated to dull redness becomes Al_2O_3.
Specific gravity after heating to 600° C becomes 2·8.
Specific gravity after heating to 1 200° C becomes 3·9.

The allotropic change-point, beyond which the oxide becomes insoluble, is given as 850° C.

The expression "totally insoluble" has, in the authors' opinion, been misleading. No substance is absolutely "insoluble." The expression "insoluble" usually means that the amount of dissolved solid is, for all practical purposes, negligible.

(2.3) Solubility of Alumina

Since the dust on and near economizer surfaces is known to contain alumina in some form of chemical combination, the reactions of alumina with sulphuric acid of various concentrations and at various temperatures were examined. As the authors suspected that the rate of attack was associated with the strength of the acid, solubility tests were carried out on pure alumina of specific gravity 3·47. The results are shown in Fig. 4.

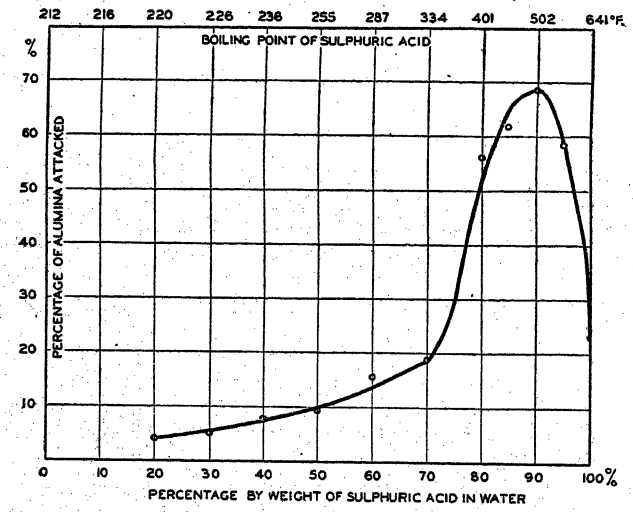


Fig. 4.—Attack of boiling sulphuric acid on alumina.

Specific gravity of alumina = 3·47.
Volume of acid = 100 cm³.
Weight of alumina = 1·0 gramme.
Time of each reaction = 20 min.

In each test 1 gramme of alumina was attacked by 100 cm^3 of boiling sulphuric acid, the controlled variable being the acid concentration. The amount of unattacked alumina was estimated after each test of 20 minutes' duration.

It will be seen that at lower concentrations the alumina is only slightly attacked. After 70% concentration an acceleration takes place, rising to a maximum at 90%. Thereafter follows a sharp diminution in the rate of attack with pure acid of 1·84 specific gravity.

These tests were not, however, confined to the action of sulphuric acid on *pure* alumina; it was realized that alumina does not exist in the pure state in coal ash. Similar tests were carried out on flue dust of various kinds. All the results demonstrated that the curve for *pure* alumina, Fig. 4, was typical whether the alumina was pure or in certain combined states. In this connection it should be added that further information is required on the actual condition of the alumina in coal ash, when subjected to the various temperatures occurring in a boiler plant.

* *Loc. cit.*, p. 878.

From all these considerations and experiments the authors conclude:—

(*a*) That the solubility of the aluminium compounds contained in flue dust depends on the temperature to which the substances have been heated before they come into contact with sulphuric acid.

(*b*) That the rate of attack increases as the temperature and strength of the acid increase, up to a concentration of 90%.

(2.4) Solubility of Aluminium Sulphate

The next matter calling for investigation was the solubility of aluminium sulphate in sulphuric acid, and appropriate tests were made. Fig. 5 shows the results. As the acid increases in

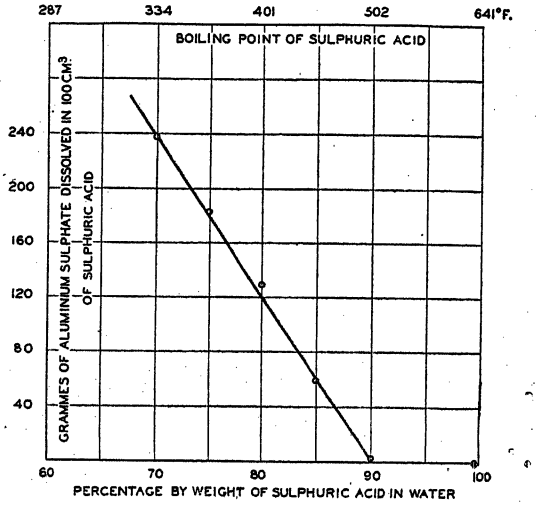


Fig. 5.—Solubility curve of pure $Al_2(SO_4)_3 . 18H_2O$ in boiling sulphuric acid of various concentrations.

strength the solubility decreases, or, in other words, the amount of aluminium sulphate which can be held in solution becomes less. Thus, if the acid concentration of a saturated solution of aluminium sulphate in sulphuric acid is increased, some aluminium sulphate will be thrown out. It will be shown later how this consideration of the solubility of alumina compounds not only contributes to the explanation of the behaviour of dust from pulverized-fuel firing, but may prove of value in devising methods for the prevention of deposits from stoker-fired plants.

(2.5) Occurrence of Sulphuric Acid on Economizer Surfaces

If the theory which is being developed is to fit the facts, and since the action of *dilute* sulphuric acid on alumina is negligible even over long periods, it must now be shown how the conditions necessary for the formation of *strong* sulphuric acid on economizer tubes may arise.

It is known that when an economizer first goes into commission it may have a long period of immunity from bonded-deposit accumulation. This is ascribed to the absence of any sulphuric acid films on the tubes; such a film must exist before the growth of deposits can commence.

The only direct source of sulphuric acid is the sulphur trioxide in the gases. The necessary moisture can be deposited only when the tubes are at a temperature below the dew-point of the gases. It is appreciated that the latter conditions should apply but rarely in the case of power station economizers, but it may be that in some instances, where a plant has been started up with cold water, many months of possible immunity from bonded deposits have been sacrificed in a short time. This point will receive fuller attention later.

In general, however, it is true to say that power station economizers work with water temperatures well above the moisture dew-points of the gases.

The authors imagine, therefore, that the process is on the following lines: During the period of immunity the economizer tubes are gradually directly attacked by the gases containing small amounts of sulphur trioxide and water vapour. Ferrous sulphate is formed, and this oxidizes to ferric sulphate. During this comparatively long period, however, the surface of these tubes appears to be perfectly clean, since the ferric sulphate is present only in minute quantities.

Ferric sulphate, however, is not only deliquescent but is a powerful catalytic agent capable of converting sulphur dioxide into sulphur trioxide. This fact was known and recorded many years ago.* Thus once a small deposit of ferric sulphate has been formed, the local "manufacture" of more sulphuric acid from the relatively plentiful supply of sulphur *dioxide* and moisture can proceed at an accelerated rate.

There is, therefore, after a long period of what has been termed "immunity," a thin film of sulphuric acid on the economizer tubes. This film collects a minute covering of flue dust or fly ash. If the acid concentration is sufficiently high, the dust may be attacked, aluminium sulphate formed, and the particles may be cemented together sufficiently to prevent their being dislodged by soot-blower action.

The question here is clearly one of requisite acid concentration. The strength of the sulphuric acid appears to be directly related to the temperature of the metal of the tubes. It is known that sulphuric acid is formed by the catalytic process already mentioned, the constituents available being the sulphur dioxide and the water vapour in the gases. It is known that the boiling point of sulphuric acid rises with the concentration (Fig. 6), and that

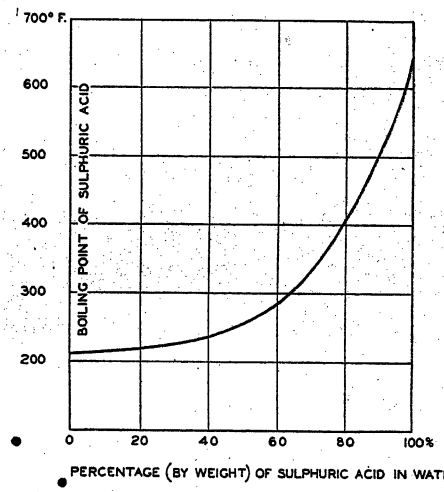


Fig. 6.—Boiling point of sulphuric acid of various concentrations (after Lunge).

to each concentration there is a definite temperature at which the acid on the tube is in equilibrium with the sulphuric acid vapour. It should be noted that even an acid of 80% concentration (by weight) has quite a low vapour pressure, and this is depressed still further in the presence on the tube of acid-soluble compounds.

At any given temperature, therefore, there must be a definite acid concentration on the tubes. Were the acid at a given temperature more dilute than shown by Fig. 6, water vapour would be evolved because the temperature would be higher than that corresponding to the boiling point of the dilute acid. Conversely, a stronger acid would pick up moisture from the gases until equilibrium was reached.

Thus at any given point in the economizer where acid "manufacture" is taking place, the strength of the acid will depend only on the temperature conditions prevailing on the metal surface or in the deposit. The specific quantity of acid at any particular place will depend on the rate at which the "manufacturing" reactions are taking place, and on the character of the gaseous constituents in contact with the actual metal. It should here be noted that a deposit does not prevent the gases from making contact with the tube metal; examination shows that even bonded deposits are porous to gases.

The sulphuric acid graph in Fig. 6 explains why bonded deposits occur on economizer tubes and not on metal parts adjacent to the tubes. Where a metallic surface is not kept at a temperature below that of the local gas stream, it ultimately attains to and remains at that temperature. No sulphuric acid can form on a surface much above 640° F, the approximate boiling point of pure sulphuric acid. Any dust collecting on such surfaces remains as dust, and is practically unchanged throughout the run of the plant.

Thus, in the metal parts adjacent to the economizer tubes the pre-requisite condition for bonded-scale formation—the initial sulphuric acid film—is necessarily absent. Such surfaces may collect dust, but the deposit remains dust and does not bond.

It will be clear from what has already been said that the dew-point of the gases is but a minor consideration. It is not even a measure of the water vapour present and taking part in the reaction, since the dew-point is very much modified by the presence of small quantities of sulphur trioxide.

(2.6) Power Station Conditions

It is now possible to offer an explanation of the fact that the hard bonded deposits appear to form almost exclusively under power station conditions. It has been shown that the local strength of the sulphuric acid present on an economizer tube surface—or in the deposit—depends on the local temperature. The higher the temperature, the stronger the acid (Fig. 6).

It has also been shown that only fairly concentrated acids will attack the alumina compounds carried by the gases, sufficiently to produce the quantity of aluminium sulphate needed to form a bonded deposit (Fig. 4).

It follows, therefore, that the hard deposits will form only under those conditions where the economizer tube temperatures are high enough to ensure the formation of acids of the requisite strength—that is, in the temperature range between 250° F and 450° F. This is what has been termed the "power station range," and is the characteristic which chiefly distinguishes "power station" from "industrial" conditions.

(2.7) Stalagmitic Deposit Formations

The development of the theory has now arrived at the stage where it is possible not only to explain the stalagmitic scale formation, but to reproduce in the laboratory the typical characteristic formation shown in Fig. 3.

Observation shows that when a deposit is very thin it is fairly smooth and has a uniform thickness. The underside is in contact with the tube metal, and is at the same temperature as the tube. It is in this region that most of the sulphuric acid "manufacture" takes place, the strength being governed, as already explained, by the local temperature. Examination of the thin deposit next to the tube metal reveals, as might well be expected, the presence of ferric sulphate and of free sulphuric acid.

According to the authors' theory, the sulphuric acid is sufficiently strong to attack some of the alumina compounds in the fly ash which has adhered to form the initial thin smooth layer.

* H. F. JOHNSTONE: *loc. cit.*, 1931, 28, p. 45.

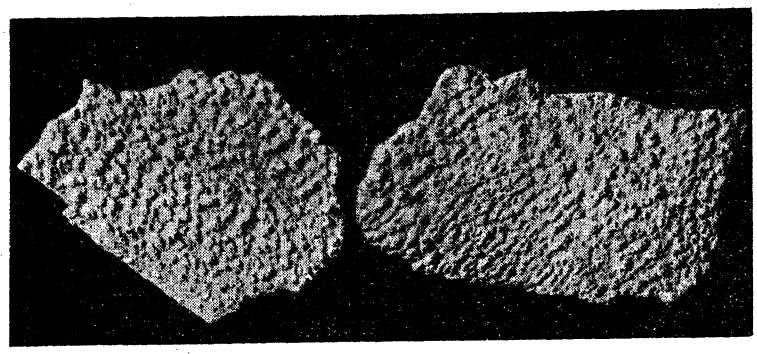


Fig. 7.—Scale $\frac{1}{16}$ in thick (full size). Beginning of stalagmitic growth.

As the acid continues to form, it seeps upwards through the scale. The temperature obtaining on the gas side of the scale is naturally higher than that on the tube side; scale, though porous to acid and to gases, is not a good conductor of heat.

The acid, saturated with aluminium sulphate, becomes supersaturated at the deposit surface, and the excess sulphate is thrown out at the hottest part of the deposit, since stronger acid cannot hold as much sulphate as the weaker acid (Fig. 5).

A small amount of hydrated aluminium sulphate thrown out of solution on the deposit surface is immediately subjected to the high gas temperature; it swells up, passes through the glutinous stage, traps a few particles of fly ash and hardens off. The particles caught, form as it were peaks facing the gas stream; the deposit surface becomes covered with small lumps, marking the spots where the sulphate was expelled (Fig. 7). These lumps or peaks now become the hottest parts of the deposit: it is at these places that further sulphate is thrown out and that further growth occurs.

As growth advances, sulphuric acid can be formed in greater quantity, since the total amount of ferric sulphate has increased; the surface temperature increases, and the process tends to accelerate. The higher the temperature of the acid, the greater becomes its degree of concentration. The stronger the acid, the less aluminium sulphate it can hold in solution, and the more it must throw out at the deposit surface.

The process is thus one of accelerating rapidity. The thicker the scale, the more quickly further scale will form, and the rougher will be its surface (Fig. 8).

It is also now clear why the deposited scale is stalagmitic in form. The particles of fly ash come from a more or less definite direction and adhere to the temporarily sticky peaks of the deposit, causing a natural building towards the source of supply of dust (Figs. 9 and 10).

The various processes described are taking place at the same time. Sulphuric acid is being manufactured at the base of the deposit by the catalytic action already explained. The strength of the acid is controlled by the local temperature, and where feed temperatures are high—between 250° F and 400° F—the acid strength is great enough to take alumina into solution. It should here be noted that it is only where the tube metal is at a sufficiently high temperature—as under "power station" conditions—that an acid sufficiently strong to dissolve alumina can be formed.

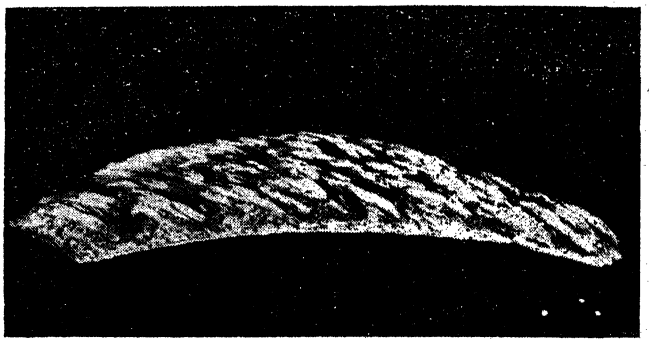


Fig. 9.—Section of deposit (× 1½) cut in direction of gas flow.

Hence, an economizer which remains "clean" for 6, 12 or 20 months, accumulates a thin, smooth scale, and then rapidly fouls with a hard, bonded, rough, stalagmitic deposit at an increasing rate.

The theory, as enunciated so far, therefore satisfies criteria "A" and "C."

(2.8) Experimental Demonstration

The process is capable of being demonstrated in the laboratory.

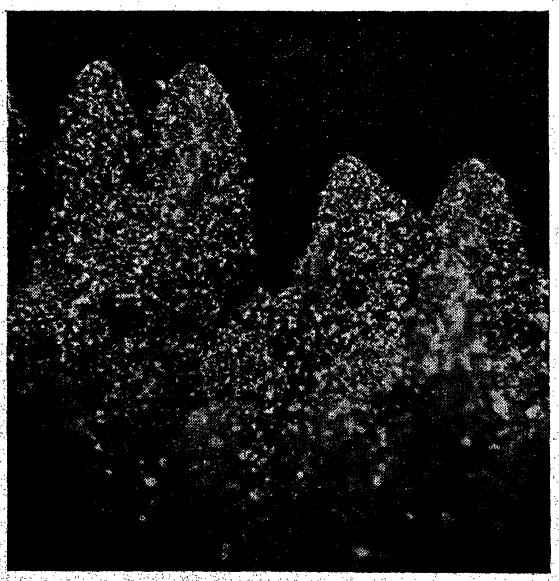


Fig. 8.—Coarse deposit (× 20) showing well-developed stalagmites covered with small particles of dust.



Fig. 10.—Section of deposit (× 25) cut at right angles to the direction of the gas flow.

A small slab of "deposit" was prepared, by making a paste of a typical fly ash and 80% sulphuric acid. This was slowly baked at a moderate temperature until it hardened.

A solution of sulphuric acid containing aluminium sulphate was then gradually introduced to the underside of the slab, to reproduce the conditions in actual service. This was done by allowing one edge of the slab to touch the surface of the acid solution contained in a porcelain dish. The idea was to accelerate the process to enable a laboratory deposit to be built up much more quickly than in service.



Fig. 11.—Artificial deposit (full size).

A stream of hot air (at about 800° F) carrying fly ash particles was then directed obliquely on to the surface of the slab. The result was surprising. Small lumps quickly appeared on the deposit surface, the high points were seen to swell up, become momentarily sticky, entrap further particles, become sticky again, and grow forward to give the familiar form of the many samples from actual service.

The process of growth and the stalagmitic and ripple formation could actually be watched as they proceeded. The transition from slow growth to rapid coarsening of the structure was easily observable. Fig. 11 shows artificial deposits built up in this way.

A graphical presentation of the whole range of economizer deposits is given in Fig. 12.

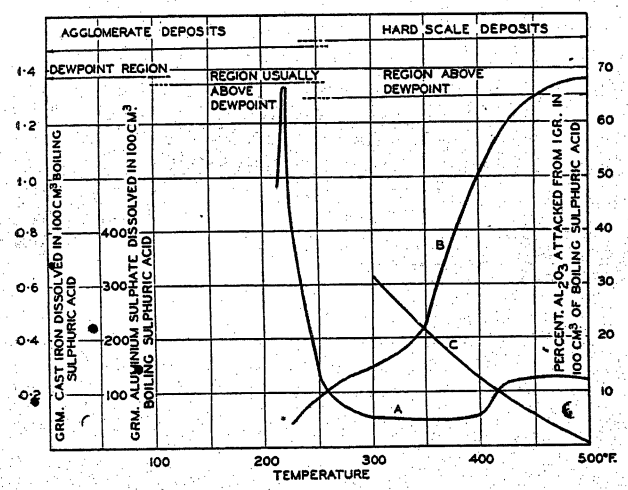


Fig. 12.—Composite diagram correlating the reactions in the economizer range.

Curve A.—Solubility of cast iron in sulphuric acid.
Curve B.—Attack of alumina by sulphuric acid.
Curve C.—Solubility of aluminium sulphate in sulphuric acid.

The three curves in Figs. 4, 5 and 13 have been replotted on a temperature basis, and thus indicate the temperature conditions which correspond to the three main types of deposit:—

(*a*) Agglomerate deposits in the true moisture-dewpoint range, where the "bond" is carbonaceous matter, corrosion products and moisture.

(*b*) Agglomerate deposits in the range usually above the moisture-dewpoint, the "bond" being chiefly iron salts and occasionally carbonaceous matter.

(*c*) Hard bonded deposits in the range always above the moisture-dewpoint, the bond being aluminium sulphate.

Ranges (*a*) and (*b*) correspond roughly to "industrial" conditions, whilst range (*c*) corresponds to "power station" conditions.

(2.9) Pulverized Fuel

It is still necessary to explain the comparative immunity of pulverized-fuel-fired plants from bonded economizer scales, as required by criterion "B."

It is well known that the fly ash from such plants consists largely of hollow spherical particles. These particles, since they *are* spheres, must have solidified before they reached the economizer.

From what has gone before, it will appear that, in order to form a bonded deposit, these spheres would have to be appreciably attacked by sulphuric acid.

There are, however, two factors operating against such attack. Other workers have noted that there is less sulphur trioxide in the gases from pulverized-fuel firing than in those from stoker

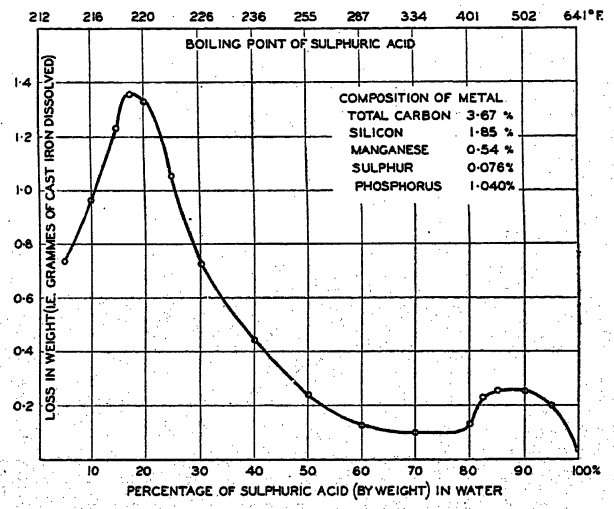


Fig. 13.—Action of boiling sulphuric acid on cast-iron test pieces, 1·515 in diam., 0·376 in thick, with hole 0·25 in diam. Time of immersion—4 minutes.

firing. The relative scarcity of sulphur trioxide would greatly increase the "immunity period."

There is, however, another important factor. It has been shown that, although a hydrated alumina is appreciably soluble in strong acid, a partly or completely dehydrated alumina is much less soluble. Each small grain of ash in a pulverized-fuel-fired plant has been subjected to a very high temperature—high enough to fuse and "spheroidalize" quite refractory ashes. It would seem, therefore, that the ash from pulverized-fuel plants may contain aluminium compounds in comparatively insoluble forms.

Unless, therefore, a pulverized-fuel installation were run for a very long time, it is unlikely that a bonded deposit could be made to form on the economizer tubes. The "immunity period" during which the minute quantities of sulphuric acid in the gases collect on the tubes, is very much longer, by reason of the scarcity of sulphur dioxide. When the film does form eventually the alumina in the fly ash is practically immune from attack, and the aluminium sulphate reaction never takes place.

The authors hold, therefore, that the theory satisfies criterion "B" in that it explains the immunity of pulverized-fuel-fired plants from bonded economizer deposits.

(3) PREVENTION OF BONDED ECONOMIZER DEPOSITS

In so far as the availability of a boiler unit depends on preventing the accumulation of bonded deposits on the economizer, the investigations which have been described, and the conclusions which have been reached, point clearly to certain ways of preventing the formation of these deposits.

The cycle of processes involved in bonded-deposit formation may thus be summarized:—

(*a*) Formation of the original thin film of sulphuric acid from the SO_3 and moisture in the gases.

(*b*) Attack of the iron of the tube by the acid, with the formation of ferrous sulphate oxidizing to ferric sulphate.

(*c*) Formation or "local manufacture" of more sulphuric acid from the sulphur dioxide and moisture in the gases, by the catalytic action of the ferric sulphate; the acid strength being dependent on the local temperature.

(*d*) Adherence of some fly ash particles to the thin acid film.

(*e*) Attack by the strong acid on the alumina in the fly ash.

(*f*) Formation of aluminium sulphate which is eventually thrown out on the deposit surface.

(*g*) Heating of the surface sulphate with local swelling, and presentation of a glutinous area to fly ash particles.

(*h*) Capture of more fly ash particles and growth of stalagmitic projections.

If any one of these stages can be inhibited, the subsequent stages can be prevented from occurring. The earlier in the series the inhibition can take place, the better the result, and for present purposes only the first three stages need be discussed. The later stages present the problem of deposit removal rather than that of deposit prevention.

Stage (a).

It is not practicable to eliminate the sulphur from the fuel. On the other hand, pulverized-fuel firing, as already explained, does appear to reduce the proportion of SO_3 present in the gases, and this delays the formation of the initial film.

It may be that the processes involved in stoker firing can be modified in some way which will increase the proportion of spheroidalized fly-ash particles, and decrease the proportion of "irregular" particles. If such spheroids contained the alumina compounds in a form less readily attacked by strong sulphuric acid, the "immunity period" could possibly be greatly increased.

The authors do not propose to follow this line of thought further at the present time, but it does seem to be a promising avenue of research, satisfactory results from which could have beneficial effects beyond the limits of the economizer itself. Such considerations are matters affecting future design; there are other implications of the theory which have immediate importance in existing plants.

There should here be emphasized a warning already uttered. It is a general experience that an economizer will run for many months before the first signs of a bonded deposit are observed. There have, however, been cases where this intractable type of deposit has formed at a much earlier period, and it will be useful to inquire into causes.

It sometimes happens that a new unit is started up with "cold" water. Possibly only water at 60° F or so is available, and it is thought that in a few hours the water will be warmed up and the plant running normally with no damage done. On the contrary, a great deal of damage may have been done. Cold economizer tubes exposed to the products of combustion from the boiler furnace—whether during starting-up or "floating the valves"—will condense moisture in a few minutes. The moisture absorbs sulphur compounds; dust in minute quantities adheres to the moist surface; and under such conditions the assembly of ingredients which would otherwise take months to complete is achieved in a short time and the immunity period may be lost.

In no circumstances should an economizer be fed with cold water when the gases are passing over the tubes. If the reasons are understood, the difficulties in making the necessary arrangements will be overcome. The bypass flue should be used if hot water is absolutely unobtainable, but since dampers are seldom really gas-tight this procedure is not a complete guarantee against moisture condensation.

The authors have confined their remarks to the problem of economizer fouling, since their investigations have been carried out chiefly on economizer deposits. At the present stage they refrain from extending their conclusions to air-heaters and to certain portions of the heating surface of the boiler proper, although little consideration is needed to show the applicability of their findings in those directions.

Stage (b).

Once the acid has been deposited on a cast-iron or steel surface the iron will be attacked with greater or less severity, depending on the temperature conditions and on the strength of the acid. A series of tests was conducted to confirm what is more or less general knowledge—that as the strength of the acid increases, the degree of attack on cast iron decreases. The experiments were carried out with various strengths of boiling sulphuric acid, and the results are shown in Fig. 13.

The conclusions to be drawn from this curve are interesting. In those high-temperature regions of an economizer where the deposit is hardest, one would expect the degree of attack on the local iron surfaces to be least. This is confirmed by experience in all the deposits examined where the exact provenance was known. It would appear, however, that even at the highest temperature shown in Fig. 13, and with the strongest acids, there is a sufficient formation of ferric sulphate to ensure catalysis and a continuous "manufacture" of acid of strength high enough to attack the aluminium compounds.

The maximum point on the curve, i.e. at 219° F, must not be confused with "maximum corrosion." Maximum corrosion in economizers occurs at temperatures below 120° F, when moisture from the gases deposits on the tubes, a genuine case of "dew-point."

It should be noted that ferric sulphate will also form from the iron content of the coal ash. It is known* that iron compounds in ash depress the fusion temperature. It has also been suggested by several observers that rapid fouling of economizers is in some way related to a low ash-fusion point. It now seems clear that deposit growth and low ash fusibility may both be related to the iron content of the ash, and that this is probably the only connection between the two properties.

From what has gone before, it will now be realized that the authors' proposals for ensuring a high economizer availability are essentially simple. Attention has repeatedly been drawn to the fact of experience that it is usually many months before bonded scales form on economizer surfaces. It is now asserted that if an economizer will run for 12 months without a bonded scale forming, then there is no reason why such a scale should ever be allowed to form. Every boiler has to be shut down annually for inspection, though the permissible period between thorough inspection may be somewhat increased in special circumstances. If on these occasions the economizer is restored to its initially clean condition, it should run without bonded deposit formation until the next annual period of inspection and overhaul.

* J. S. S. BRAME: "Fuel," 2nd ed., 1919, p. 41.

It is important to make sure that the economizer is really *clean* down to the metal, and that all traces of sulphuric acid and iron sulphate have been removed. An economizer which "looks clean" may have a scale 0·01 in thick already formed.

Rodding, brushing, hand-lancing, and similar methods are quite insufficient. So far as is known at present, thorough washing is the only way. To ensure such washing it is essential to test the metal surfaces at intervals for acid and sulphate until the result is satisfactory. Any chemist can devise suitable tests to conform to particular requirements.

The authors' preference is for washing with plain water. The addition of "neutralizing agents" may have an effect opposite to that intended. The use of lime in one form or another would probably cause an insoluble film of calcium sulphate to remain on the metal. If soda ash is used the sodium sulphate has still to be removed, and if the water will remove the sodium compounds it will remove the acid and the iron salts. The difficulty with soda ash is that it causes the gelatinous hydrate of iron to form and stick tenaciously to the tube surfaces. If allowed to remain, this hydrate film will readily pass to the sulphate form as soon as the plant is put into commission, and deposit growth can commence at once.

The essential point is to ensure the removal of the sulphur compounds, and not merely to "neutralize" them where they are found.

An installation recently visited by the authors was a good example of the stage appropriate for washing. For 4 months prior to the visit the plant had been out of commission every month or so, and had started up on each occasion with feed water at about 100° F. The feed, after passing through the economizer, entered the boiler at a maximum temperature of 365° F, the inlet temperature during normal working conditions being about 200° F.

These conditions resulted in the formation of a thin film of corrosion products on the economizer tubes. The soluble portion was found to be nearly 40% of the total deposit, the constituents being:—

Hydrated ferrous sulphate	3·77%
Hydrated ferric sulphate	8·42%
Hydrated aluminium sulphate	11·55%
Excess sulphuric acid	14·82%

This was a case where the oscillating temperature conditions had reduced the immunity period considerably; the sample of scale was taken just prior to the time when a deposit with an aluminium sulphate bond could be expected to form with accelerating rapidity.

The economizer surfaces *looked* comparatively clean and such as to give rise to no undue perturbation. The constituents necessary for the formation of heavy deposits were nevertheless already in position. Water washing quickly and easily removed the entire film. The authors are not able at the moment to give particulars of the extent of the further immunity period, as several months must elapse before results can be observed.

(3.1) Influence on Construction and Design

The emphasis placed on the need for thorough washing leads to a consideration of economizer design. Washing down is no new process: it has often been adopted for the removal of deposits already accumulated. The present proposal is for washing down to prevent deposit accumulation.

Experience with washing away deposits has made it very clear that some economizers are much easier to wash than others. A deep bank of closely spaced tubes is more difficult to wash thoroughly than a series of shallow tiers. Circular tubes are in any event not easy to wash thoroughly all round. Special forms involving water pockets should be avoided at all costs if the proposals for "pre-washing" are adopted. Such pockets introduce the possibility of hidden corrosion.

It would seem that shallow, accessible tiers or banks of tubes are an advantage. Tube form is important here, that construction being most suitable which lends itself to the thorough cleaning and examination of all parts of the gas-swept surfaces. The authors' preference in this connection is for staggered tubes.

As regards tube form in general, it may be said that bonded scale formation appears to be quite independent of the shape of the tube. This deposit collects on plain round tubes, in straight rectangular or cylindrical gas passages, and on tubes with gills of rectangular, circular or other form.

Experience has shown that certain tube shapes are less prone to collect dust than other forms. The authors find that the degree of proneness to collect dry dust and grit bears no relation to the proneness to bonded deposit formation. If the other conditions favour the accumulation of bonded deposits, then the tube form is unimportant; bonded deposits will accumulate.

It need hardly be added that after an economizer has been washed, it should be thoroughly dried out before going into commission. Nor, from what has gone before, need it be emphasized that the drying must on no account be done by passing gases through the economizer.

The simplest way is probably to circulate hot water or steam through the tubes. This may involve special piping connections for the purpose, but these need present no great difficulty.

Provision must be made for dealing with the waste water. Sluicing down should be generous. Plenty of water is needed, and has subsequently to be led away to drains. It is here that the boiler designer can simplify matters by arranging boiler, economizer and air-heater so that the gases preferably pass downwards through the economizer and upwards through the air-heater, with a hopper beneath the region where the gases change direction. This hopper would then serve both economizer and air-heater. Full-way valves in the base of the hopper can then be accommodated, and the rest is a matter of piping. This kind of arrangement is by no means new, and where it exists the authors' proposals can be adopted at once without difficulty.

As regards constructional materials, it need hardly be said that cast iron is by far the best for hopper bottoms and drain piping. In some instances the inner casings of the economizer chambers are made of cast iron, to enable washing to be carried out without fear of corrosion. Such arrangements, though perhaps more expensive than the usual thin steel-plate casings and hoppers, are admirable for the purpose and quickly repay their extra cost.

It has already been indicated that washing-down is no new process, although plants which have hitherto been designed for ease in washing have been so constructed with the idea of deposit removal. Where these advantages of cast-iron casings, hoppers and drains exist, the plant is in the fortunate position of being able to take advantage of the pre-deposit washing proposals, and thus, by a comparatively simple modification of operational method, to secure greatly enhanced availability.

(3.2) Influence on Future Arrangements

The design flexibility, as it were, of the modern economizer, more especially of the steel-tube type in which the tubes are protected by external cast-iron gilled sleeves shrunk in position, has been fully recognized by boiler designers.

The manner in which this flexibility has been employed has not always, however, tended to improve availability. Whereas the demands of the combustion chamber, the boiler drums and superheaters have, in many instances rightly, been dominant factors in determining the disposition of the several parts, the various tube lengths, widths and heights permissible in the

economizer have been manipulated rather to make the latter fit the space left over than to secure maximum availability.

In many recent instances it has been possible to reconcile the conflicting claims of the boiler and its auxiliaries to ensure, among other desirable things, long operational periods at high efficiency.

It is now suggested that much more attention should be paid to arranging the economizer in such a way that it can be conveniently washed. It is probable that similar provision for the air-heater would have similar advantages, but it is important that the air-heater should have a separate hopper, and that it should on no account be arranged immediately above the economizer.

(4) THE REMOVAL OF BONDED DEPOSITS ON ECONOMIZERS

There are probably certain cases where simple washing during the "immunity period" is difficult or impossible. There are other cases where deposits have already accumulated, and the removal of such deposits constitutes a problem of greater or less importance, depending on the quantity and character of the deposit, on the type and arrangement of the economizer and on the general facilities available.

It is never an easy matter to remove a thick, intractable bonded deposit from an economizer consisting of a large number of closely pitched tubes. To chip off the scale by hand or by some improvised equipment is an arduous, lengthy and seldom satisfactory method. With deep banks of tubes it is often impossible effectively to remove hard scale from the less accessible parts.

Washing-down is frequently tried, and if the deposit is of such a nature as to sludge or crumble away when wetted, the application of copious quantities of water may give good results.

It is when the scale is of the hard bonded nature described in Section 2 that difficulties arise. This is often a matter for surprise, especially where small samples of scale detached by hand have been dropped into water, and have appeared to disintegrate readily. Such tests may be most misleading, since the deposit may be porous to water from its underside. The conditions of the sample test are quite different from those on the economizer itself, where the underside of the scale cannot be reached except through the surface.

Of the various washing processes which have been applied to overcome this difficulty, the use of caustic soda solution has been the most successful, perhaps because aluminium hydrate is soluble in excess of such a solution.

A bonded deposit can, however, usually be softened by *gradual* moisture absorption. Two methods are known, and both have been applied with success.

(*a*) *Steaming Method.*

This involves steaming or "cooking" the economizers for periods of 24 hours or more. The scale is given a gentle steam bath, usually by introducing a number of perforated pipes below the economizer tubes, and allowing the whole chamber to be subjected to a steaming atmosphere whilst avoiding profuse condensation of moisture on the scale. The latter can be avoided by keeping the economizer tubes filled with warm water.

After a sufficient period has elapsed, the scale is usually soft enough to be washed away in one good sluicing. If not, the treatment has to be repeated until the desired result is achieved.

This steam treatment may also be useful in conjunction with deposit-prevention washing. If the initial ferric sulphate deposit on the tubes has become completely dehydrated, it will be difficult to dissolve. "Steaming" it renders the ferric sulphate more easily soluble, and it can then be readily washed away.

(*b*) *Wetting and Warming Method.*

This method involves damping the deposit with a fine water spray. Hot water is then passed through the economizer tubes until the deposit either cracks off or softens sufficiently to enable washing to be successful. A repetition of the process may be needed, as also the assistance of rodding, brushing and hand-cleaning generally.

The insufficiency of "dry" cleaning will be apparent from a consideration of the process by which bonded deposits are formed. Plain-tube economizers are occasionally cleaned by rubbing chains over the surfaces and thereby cracking off and removing the scale. Apart from being a particularly unpleasant and arduous operation, this process tends to leave on the tubes a thin covering of ferric sulphate, the presence of which considerably reduces the subsequent immunity period.

Where hand-removal of a bonded deposit is adopted, it should be followed by liberal sluicing with water to remove all traces of ferric sulphate and sulphuric acid, and, for reasons already given, the use of "neutralizing" agents must be avoided.

(4.1) The Use of Soot-Blowers in Economizers

This subject has received much attention in recent years, and particular mention must be made of Glinn's paper on "The Soot Blower."* Many designs and systems of soot-blowers have been produced and tried, but it cannot be said that the problem of keeping clean boiler, economizer and particularly air-heater surfaces by soot-blowing equipment has been finally solved.

From the economizer standpoint the position at the present time can be summarized thus:

(*a*) Almost any well-designed soot-blowing equipment will remove loose dust and non-bonded deposits from economizer heating surfaces. Service troubles with such blowers are generally of a mechanical nature.

(*b*) No soot-blower at present available, however powerful, will remove or prevent the formation of bonded deposits where conditions are favourable to the latter.

(*c*) In many cases a reduction in the frequency of soot-blower operation has been found to give good results, and certainly it effects economies in steam.

The first two points are facts of general experience, and call for no extended discussion. The third point, however, is the subject of much argument. There appears to be no general principle which satisfactorily accounts for the undoubted fact that, in some plants, the rate of formation of bonded scale is apparently retarded by reducing the frequency of blowing from once in every 8 hours to once a day.

The authors do not attribute much importance to the temporary increase in the moisture content of the gases during the blowing operations. The actual percentage increase is small, and bonded scale formation is not primarily a moisture-dewpoint phenomenon. Further research on this aspect of the subject is required.

(5) ACKNOWLEDGMENTS

The authors wish to express their thanks to the Directors of Messrs. E. Green and Son, Ltd., Wakefield, for permission to publish the results of their investigations, and also to record their appreciation of the assistance given by many power station engineers. Their cordial thanks are also due to their colleagues, in particular Mr. C. W. Parris and Mr. E. Raper, for the many ways in which they have assisted.

* *Journal I.E.E.*, 1942, 89, Part II, p. 533.

CAUSES OF HIGH DEW-POINT TEMPERATURES IN BOILER FLUE GASES

By W. F. HARLOW, Wh.Ex.*

(ABSTRACT† *of a paper which was received by The Institution of Mechanical Engineers 18th August, and read at a joint meeting of The Institution of Electrical Engineers with The Institution of Mechanical Engineers 4th November*, 1943.)

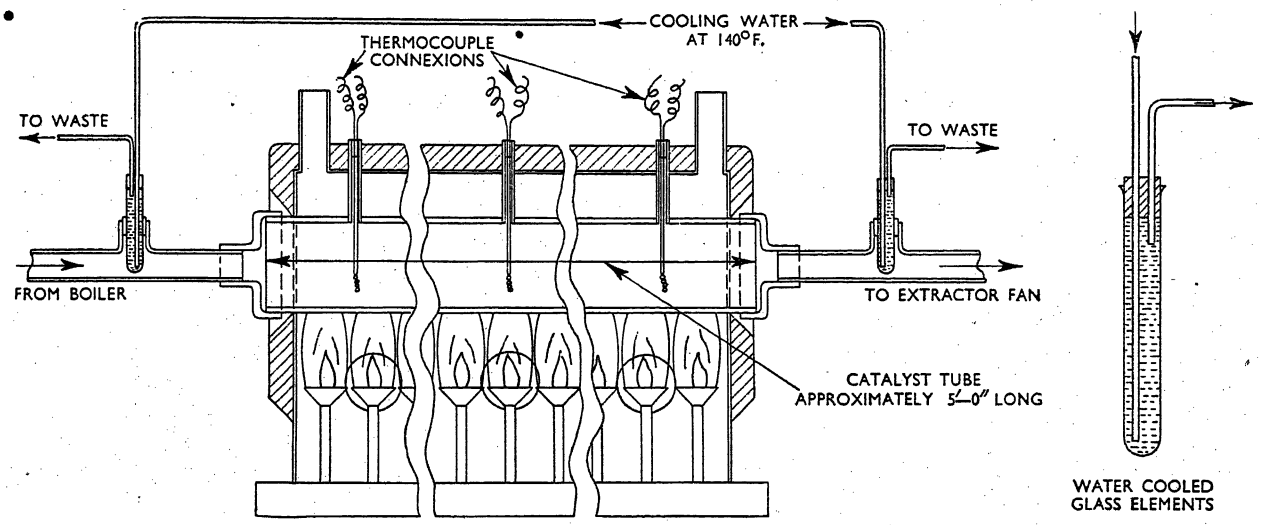


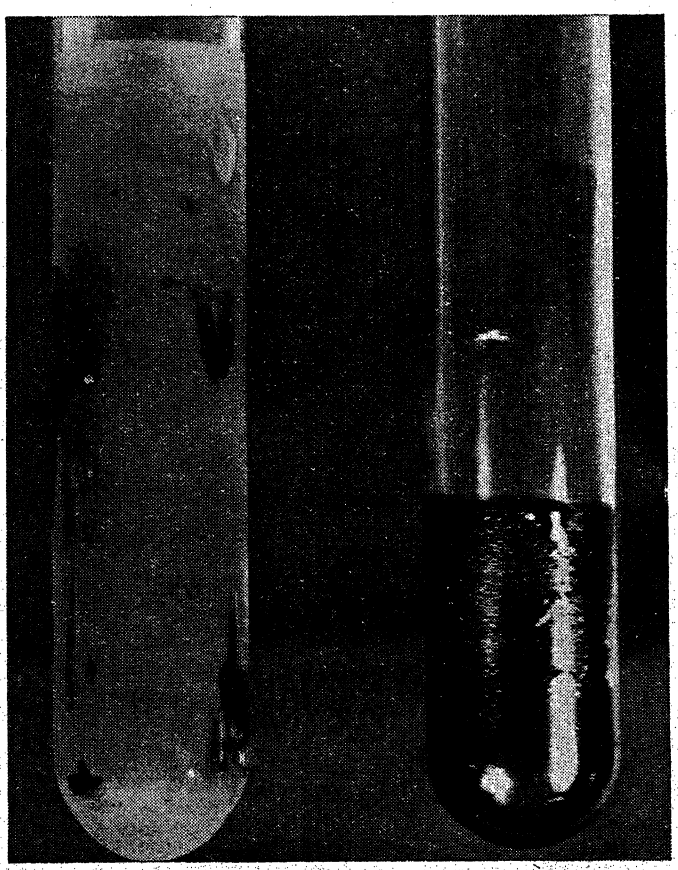
Fig. 1.—Sectional diagram of apparatus.

This paper deals with the reasons for the premature formation of acid condensate from furnace gases, resulting in corrosion and deposits on the cooler surfaces, particularly the air heaters, of modern boiler plants. Over the past 12 years the difficulties of avoiding such conditions have steadily increased, particularly in stoker-fired units. The experiments described are thought to shed on this problem new light which may lead to a solution.

Briefly, accumulated experience, together with scientific considerations, indicated that an increase in the dew-point of flue gases was sometimes occurring during their passage through the boiler, and this was thought to be due to the production of sulphur trioxide by catalytic action. It was therefore decided to test this by passing flue gases having normal dew-point characteristics over the various materials present in the boiler passes, when heated to the temperatures they are likely to acquire in a modern plant (see Fig. 1).

As will be seen, the apparatus was quite simple, the relative changes in the dew-point conditions of the flue gases being determined by the amount of acid formed on water-cooled elements having the same surface temperature. This method avoided difficult and controversial measurements of sulphur trioxide content and dew-point temperature, and at the same time gave a positive indication of the dew-forming properties of the gases.

It was found that rusty mild steel, superheater scales and firebrick, when raised to a sufficiently high temperature, were each capable of elevating the dew-point of the flue gases as indicated by an increase in acid formation. This was particularly evident in rusty mild steel when heated to 1 000° F (see Fig. 2). The variation in the amount of acid produced is shown in Fig. 3, from which it is evident that, over the temperature range tested, by far the greatest effect is produced by the rusty mild steel. With this material, a small but gradually increasing amount of acid was formed, even at comparatively low temperatures



Before After

Fig. 2.—Deposit from gases before and after passing over the catalyst.

* International Combustion, Ltd.

† The paper will be published in full in the *Proceedings* of The Institution of Mechanical Engineers.

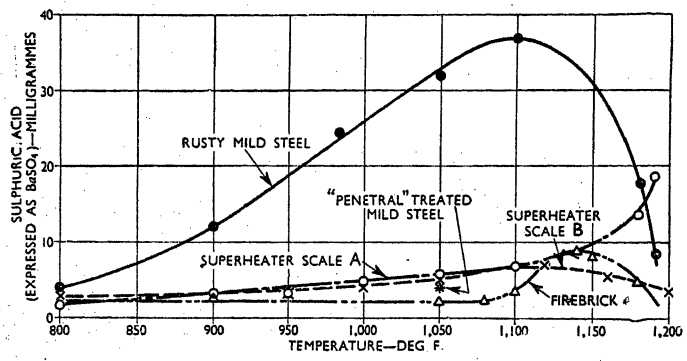


Fig. 3.—Variation in weight of sulphuric acid with temperature.

Rusty mild steel.
Firebrick.
Superheater scale A.
Superheater scale B.

(Fig. 4), which increased sharply from 800° F to 1 100° F, after which it decreased.

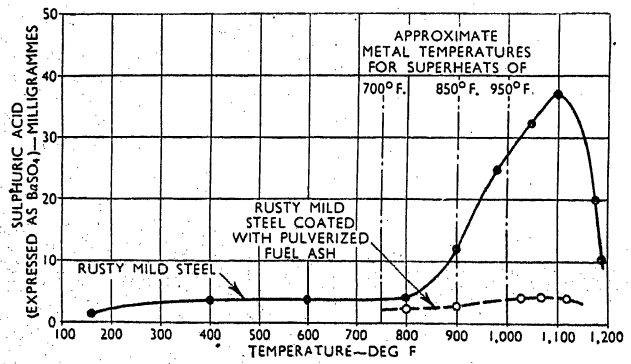


Fig. 4.—Variation in weight of sulphuric acid with temperature.

It is, of course, common knowledge that iron oxide and refractory materials are catalytic to gaseous reactions, iron oxide being used commercially in the well-known but obsolescent Mannheim process for the manufacture of sulphuric acid.

It is important to realize that 10–15 years ago superheater tubes were at a black heat, whereas to-day they are approaching a glowing condition which is favourable for both the oxide formation and its catalytic activity.

Attempts to avoid formation of acid by preventing oxidation of the steel by the flue gases at the high temperatures prevailing, showed that this was no simple matter. Nickel-plated steel, stainless steel, and steel sprayed with aluminium, all failed to resist oxidation and the resulting catalytic action.

Methods of coating the catalytic surfaces by inert material were carried out with more success, and spraying the catalyzing surfaces with milk of lime whilst they were in a heated condition definitely inhibited the acid formation. Spraying the surfaces with an aqueous suspension of pulverized-fuel precipitator dust was also found extremely effective, as shown by Fig. 4. It is thought that the blinding effect of this extremely fine dust, much of which is below 10 microns, may be responsible for the comparative immunity of pulverized-fuel plants from this trouble, high dew-point troubles being chiefly confined to stoker-fired plants.

A study of the steaming conditions and operating results of a large number of plants with which the author has been concerned shows that the incidence of this trouble is closely related to the degree of superheat temperature, on which the temperature of the exterior surface of the tube largely depends, although it will be realized that many other variables are involved.

An important example where most of these variables are common is shown in Fig. 5, which is a scale diagram of a plant

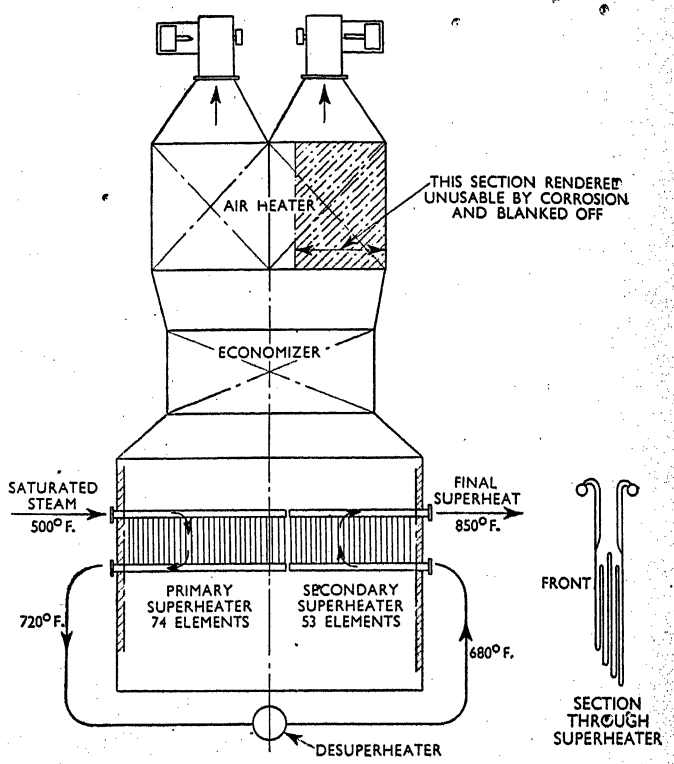


Fig. 5.—Diagram of boiler plant.
Showing arrangement of superheaters and region of air-heater corrosion.

equipped with twin stokers, each with its own secondary air fan, and a common economizer and plate air-heater, each side of which is served by separate but similar fans.

In fact the equipment of each side of the unit is identical except for the superheaters which are arranged with the primary and secondary sections side by side across the boiler, the maximum steam temperatures being 720° F and 850° F, respectively. Trouble with air-heater blockage and corrosion is only slight on the low-temperature side, but serious on the high-temperature side, where the elements have been rendered unserviceable. In certain of these units in which the handing of the superheaters is reversed, the corrosion and blockage are reversed also.

There is abundant evidence of a progressive increase in dew-point temperatures with its resulting troubles in the past 15 years, and it is considered that this is largely due to the advance in superheat temperatures. If the difficulties of maintaining air heaters in certain modern plants were experienced 20 years ago when air heaters first became generally adopted, it is doubtful whether they would be in general use to-day as an integral part of boiler equipment.

One other factor which has no doubt accentuated the trouble during the war period is the general deterioration in fuel, resulting in many cases in a higher sulphur content. It is obvious that where catalytic conditions exist, the quantity of acid produced will increase with the proportion of sulphur consumed, and the importance of using low-sulphur coals in such cases is apparent.

As stated in the paper, the experiments are by no means complete but are published at this stage in the hope they may afford immediate assistance. Investigations, in the field and the laboratory, are still being pursued, and since this paper was printed a further important and interesting fact has emerged,

namely that when the flue gases are passed over steel which has been coated with the black magnetic oxide (Fe_3O_4), such as is obtained by heating strongly in air, the catalytic action and acid formation are almost entirely inhibited over the whole temperature range. When, however, this black oxide is removed by sand-blasting and the material again subjected to the flue gases, the characteristic red oxide (presumably Fe_2O_3) appears, which has the catalytic, acid-forming effects previously referred to.

The inactivity of the black oxide may explain the immunity of new plants which is frequently observed, since new tubes are usually coated with the black oxide as a result of their heat treatment during manufacture.

The time interval necessary for this inactive layer to erode away or become otherwise displaced, thereby allowing the red oxide to form, may well represent the period during which these new plants are free from trouble.

DISCUSSION AT THE JOINT MEETING OF THE INSTITUTION WITH THE INSTITUTION OF MECHANICAL ENGINEERS, 4TH NOVEMBER, 1943

Mr. M. H. Adams: The problem of bonded deposits and corrosion of economizer heating surfaces has become much more acute in recent years; so much so, in fact, that it seems to endanger the future of stoker-fired plant. The effect on availability is also very serious, and this alone, quite apart from the loss in efficiency and the cost of cleaning, makes it essential that a solution to the problem should be found at the earliest possible moment. The problem is world-wide, and considerable efforts have been made in other countries, as well as here to relieve the situation, but without success.

It would seem as though there are a number of complex causes which key together in rather complicated and different ways before the trouble becomes manifest. If this is so, the present papers may be regarded as partial solutions of a more complicated problem. In my view the chemistry of these two papers has been so simplified and idealized as to be rather misleading. Mr. Harlow is almost certainly right in saying that sulphur trioxide or sulphuric-acid vapour is created during the passage of the gases through the superheater, but the possibilities of its formation in very much larger quantities in other ways should not be forgotten. Again, aluminium salts may act as a bonding material in the economizer, but other substances may play a similar part in other portions of the plant.

The mechanism described by Messrs. Rylands and Jenkinson is very ingenious, but I find it difficult to believe that the sulphur dioxide can find its way through $\frac{1}{2}$ in of solid scale to the tube surface. Have the authors any proof of this?

The immunity of some plants from deposits may be due to efficient soot-blowing. I remember inspecting one plant which was said to be immune from deposits, but some time before my visit a defect had developed in the soot-blowing apparatus and it had to be run at a lower pressure. Immediately the soot-blowing pressure was reduced the deposits began to form.

The authors' preventive measures seem to me, as a station engineer, to be rather impracticable. It is impossible to take the boiler and plant to pieces and carry it to the laboratory for cleaning; and I do not see how proper chemical cleaning can be done while the plant is in position. It is very difficult to clean a nest of tubes properly.

It appears that our troubles have increased with the increase in superheat temperatures, but it must be remembered that other things have altered at the same time. For instance, there is the feed temperature, which is mentioned in the paper by Messrs. Rylands and Jenkinson, and there is also the higher temperature of the boiler tubes, due to the higher pressure, and, what appears to be more important than anything else, the fact that we are trying to get more and more from a square foot of heating surface and from the grate area. Apparently it is impossible to have very high efficiency, high load factor, high rating and high availability all at the same time. The efficiency of a base-load station is of less importance than the efficiency of the area over which it operates; and if we were a little less ambitious with regard to efficiencies and ratings, and placed more emphasis on availability, we should get a better all-round efficiency.

The Boiler Availability Committee is doing its best to solve this problem, and developments during the past few months have been very hopeful. If any engineer has information which he thinks would be of use to the Committee I hope that he will make it available.

Mr. L. S. Fosbrooke: These two papers deal with a part of a very complex subject, the characteristics of modern stoker-fired combustion which result in increased boiler outage and high maintenance costs. Excessive external deposits and corrosion are attributable to the trend of boiler design over recent years, towards high duties, increased efficiency and higher steam temperatures. There is an economic limit to this development, for the great advantage of high thermal efficiency can be entirely offset, if design factors lead to increased outages and maintenance.

In his paper on the causes of high dew-point temperatures, Mr. Harlow has conclusively proved that the final steam temperature is the criterion, acting through the thermal gradient of the encrusting scales and the tube wall. The catalytic agents vary enormously in their behaviour, as is indicated in Fig. 5, and this may account in some measure for the anomalies experienced up and down the country.

The author's suggestion of injecting pulverized-fuel ash or milk of lime is not commended. When one visualizes the immense surface area in the dense tube nests of modern superheaters, it is not reasonable to expect that 100% of this will be immunized, or that the effect will remain when subjected to routine soot-blowing.

As engineers, it behoves us not to call a halt to progress and revert to less onerous conditions, but to design away from the consequences, in the light of the new knowledge on the subject. I suggest, therefore, that all new installations should be pulverized-fuel fired where the geographical and other factors are favourable. This system of combustion enjoys relative immunity from both high- and low-temperature deposits.

For stoker-fired plant, since 800° F is the critical tube-wall temperature beyond which catalytic agents become increasingly active, we should design the primary superheater only as a convection unit, with a steam temperature limitation of 750° F at m.c.r., further superheating to be done in a radiant unit disposed in the water walls at the top of the combustion chamber. With this arrangement, the gases would not intimately scrub the catalytic surface and the conversion of SO_2 to SO_3 would be negligible.

This suggestion was recently vetoed by an eminent engineer, who doubted if there was a tube material to stand up to the arduous duty of the radiant unit, but I should like the matter to be fully investigated with our present-day knowledge of high-alloy steels. American boiler makers a few years ago used an alloy of approximately 18 : 8 chrome-nickel, which was deemed suitable for an inside surface temperature of 1 150 to 1 200° F. Further, a paper in 1934 by H. G. Geer on "Superheaters for Water Tube Boilers" stated that "These experiences show that the development of high steam temperature need not be hampered by want of suitable materials and also that high-alloy steels can be

produced, which will withstand high radiation temperatures and even flame impingement." If the cost of the radiant superheater was quadrupled as compared with its convection equivalent, it would still be an economic proposition, provided it kept the boiler on line and avoided expensive renewals at the low-temperature end.

Another suggestion which merits serious consideration is that only the primary superheater should be integral with the boiler and that the final steam temperature should be achieved through an external unit, fired by either pulverized fuel or oil. Such an arrangement could be linked up with a reheating installation, but I am afraid that on a large scale layout this would lead to great complications.

Mr. F. Shakeshaft: The investigations described in the two papers give the main reasons why pulverized-fuel-fired plant is more immune from the formation of bonded deposits than stoker-fired plant. American experience, however, indicates that if the rates of combustion in pulverized-fuel plants exceed certain limits, deposits begin to form. Statistics show that quite a number of large pulverized-fuel plants are capable of almost continuous running, from one annual survey to another. A few stoker-fired boiler plants have given equal availability, but this is by no means the general rule.

In these circumstances, attention was directed to the phenomena which occur in the fuel bed of chain-grate stokers, as it was thought that, during the burning-out process of the fuel at the rear of the stoker, chemical reactions took place which might be largely responsible for some of these troubles. Recent experiments, carried out after making modifications to the air zoning of chain-grate stokers, gave promising results, enabling boilers to remain on the line for from 3 000 to 4 000 hours, instead of 600.

In one installation a high-pressure air duct is provided in order to promote intense combustion in a strongly-caking fuel bed prior to its leaving a long front arch, so that the combustion process can be completed with a very low air pressure in the remaining compartments of the stoker. In another installation with an archless front setting, the air supply to the first four compartments is isolated from the four rear compartments by means of a diaphragm provided with dampers and a slipper seal operating on the lower chain links. In practice, however, the air to the last four compartments is supplied merely by leakage through the lower links of the chain. This modification has not only permitted an increase in the maximum steaming capacity of the boiler when burning blended Welsh fuel, but has materially diminished the formation of bonded deposits. A most interesting feature of this installation is the copious formation of very fine dust immediately the firebed enters under the rear arch. The greater proportion of this dust is less than 1 micron in diameter, which is far finer than the dust usually produced on a pulverized-fuel plant and collected in the electrostatic precipitator. Observation of the fire also indicates that very little of this dust drifts back into the furnace, owing to the flow of air through the stoker into the tail-end of the furnace being reduced, and copious supplies of this fine dust are now going over the dumping bars.

During the war period, there has been a material increase in the deliveries of unwashed slacks containing large quantities of fines to selected generating stations where chain-grate stoker-fired boiler plant is installed, and this has led to a marked decrease in boiler availability. The fines cause bird-nesting in both generator tube and superheater passes, and the fine dust which is blown from the tail end of the stoker is a probable cause of bonded deposits forming on the economizer and air-heater surfaces. This experience, combined with observations on the modified stokers, would indicate the necessity for restricting the quantity of fines included in the fuel if power station output is to be maintained, and it is suggested that the proportion should be governed by the caking index and the ash content of the fines.

Mr. B. M. Thornton: My company has been operating stoker-fired high-pressure boilers with moderately high superheats for some 10 years. All these boilers are equipped with air heaters, and comparative freedom from serious fouling and corrosion troubles has often been a matter of surprise. Some 12 years ago we developed our own dew-point apparatus, which is similar in principle to the one used by Mr. Harlow. The accuracy of the instrument was established by checking the dew-point found with it by chemical and physical methods. In many hundreds of tests, the dew-point was never found to differ from the value it should have had taking into account only the water vapour in the flue gases. In other words, the influence of sulphur trioxide was in our case always negligible.

Some years ago the temperature of the superheater tubes during starting and normal running was measured by means of thermocouples peened into the tubes, and it was established that during normal running the tube temperatures were from 50° to 80° F higher than the temperature of the superheated steam. These figures confirm those given by Mr. Harlow. Our final steam temperatures varied from 780° to 820° F, and normally never exceeded 820° F. By actual test the normal highest average tube temperature was found to be about 850° F.

The curves in Figs. 5 and 6 of Mr. Harlow's paper now offer a possible explanation of our comparative freedom from trouble. It is evident that we have been working on the "safe" part of his Fig. 6; and that our experiences are some confirmation of his thesis.

It is not difficult to make and use an electrical dew-point apparatus, and it is to be regretted that so few dew-point determinations have been made in boiler houses in this country. More general investigations by those in charge of boiler houses would assist in solving some of the outstanding problems. If these problems are not solved, either steam temperatures cannot be allowed to increase above about 780° F or the exit flue-gas temperatures must be allowed to increase substantially. In either case, the firing of boilers by mechanical stokers may suffer from a disadvantage when compared with the use of pulverized fuel. Mr. Harlow's experiences are confirmed by results obtained in boiler houses in America, and especially in the Mid-Western districts.

Mr. F. Fraser Ross: Mr. Harlow's theory can be restated against the background of our present knowledge of the chemistry of sulphur in a boiler. Calculations show that sulphur trioxide and carbon monoxide should be incompatible even in proportions as low as 10 parts per million; they should react to give sulphur dioxide and carbon dioxide.

We are being asked to suppose, therefore, that the gases issuing from the combustion chamber contain virtually no sulphur trioxide or sulphuric acid, either as a result of the reaction with carbon monoxide or because none has been formed, and that some conversion of sulphur dioxide to trioxide takes place on passage through the superheater, the amount depending mainly on the temperature of the surface, but also on the time of contact and the nature of the surface. We should expect a new superheater, for example, to be a poor catalyst until its surface had become activated through time and use. This would account for the immunity period.

In any given boiler the superheater temperature, time of contact, nature of surface, etc., are reasonably constant; and, in the range of superheat common in this country, they do not vary greatly from boiler to boiler. So, on Mr. Harlow's theory,

we have in most boilers a small, constant production of sulphur trioxide to account for the observed discrepancy of a few degrees in the dew-points as compared with those calculated from the water-vapour content. Those boilers with superheats higher than normal produce much more sulphuric acid, causing a higher dew-point and a consequent tendency to air-heater trouble.

There is, unfortunately for boiler designers, a good deal of technical evidence in favour of this theory, and as far as our knowledge goes the theory is scientifically sound. Although I am not prepared to subscribe to the theory at the present stage, I cannot point to one indisputable fact against it, unless the observation that superheater surfaces are in general coated with deposit and their metal is not in any case exposed to the flue gases is regarded as such.

What is surprising, therefore, is that so far no support for the theory has been forthcoming from scientific measurements on boilers. If the theory is correct, there should be a marked difference in the sulphuric-acid content of the flue gases before and after the superheater in every stoker-fired boiler. This has never been confirmed, either by analyses of flue gases for sulphur trioxide or by the measurement of dew-points.

The great difficulties involved in these measurements make it unwise to regard those which have been made so far as damaging to the theory; but, on the other hand, until the theory has been confirmed or disproved by satisfactory measurements of this type, the unpleasant conclusion should not be drawn that superheat temperatures of above 850° F are impracticable unless a satisfactory means of coating the tube surface can be found, or unless boilers can be radically redesigned, as Mr. Fosbrooke has suggested.

Mr. R. Ll. Rees: One of the three criteria put forward by Messrs. Rylands and Jenkinson as a test for the theories of the formation of deposits in economizers is concerned with the physical structure of the scale. Their ingenious method of forming in the laboratory a scale of similar appearance does not, however, show that such a deposit cannot be built up in any other way, so that this particular criterion cannot be used as a means of judging the validity of the several theories.

Another of the three criteria is concerned with the period of immunity. It is difficult to understand why the explanation which the authors give, or a closely similar explanation, should not also be valid for other theories. Their description of the changes that may occur at the heating surface is not an essential part of the aluminium-sulphate theory, and can readily be adapted to fit others. A similar argument can be used to show that the aluminium-sulphate theory is not the only way of accounting for the comparative immunity of pulverized-coal-fired plants, which forms the authors' third criterion.

The authors give a most ingenious and valuable account of the formation of economizer deposits, but they have failed in their attempt to prove that no other theory is valid. The complexity of the problem suggests that several different mechanisms may operate simultaneously, so that there is still a wide field of ideas open for investigation.

The theory formulated by Mr. Harlow probably accounts for many instances of air-heater corrosion, but one cannot agree that this is the only possible method of formation of sulphuric-acid vapour.

The statement that "it would seem that it is impossible for an excessive amount of sulphur trioxide to be produced in the combustion process" is based upon the results of experiments made by Bodenstein and others under ideal conditions in the laboratory. The actual conditions in a boiler furnace are, however, very different. Not only is it doubtful whether equilibrium is reached, but the reactions take place at great dilution, in the presence of other gases and of finely-divided solids, and in the immediate neighbourhood of an extensive release of energy. It would be surprising if the Bodenstein curve of Fig. 1 were found to hold under conditions such as these, so that one must still consider the possibility that the gases leaving the combustion chamber may contain harmful quantities of sulphur trioxide.

Fortunately, the theory given in the paper is amenable to experimental test, and one may look forward to a definite verdict. Wherever the dangerous concentrations of sulphur trioxide are formed according to this theory, it will be necessary either to hinder the catalysis or to rest content with comparatively low temperatures in convection superheaters. If, however, the dangerous concentration is present in the gases leaving the combustion chamber, the relative freedom from this trouble, which was a feature of boiler operation up to 15–20 years ago, can best be restored by suitable modifications of the combustion process.

Mr. L. F. Jeffrey: In the long period for which I have been associated with boilers the greater part of the trouble experienced has been associated with superheaters. I should, therefore, like to know in what respect the authors feel that their investigations could be applied to the superheater.

I should like to endorse Mr. Adams's recommendation that the loads on grates should be reduced to reasonable figures, and also that the ratings of the boilers should be carefully considered. At the same time, it is felt that boiler design must receive much more careful consideration, in consultation with such investigators as the authors, with a view to eradicating those factors which contribute to the formation of dust and deposit.

It is important that, in spite of the growing popularity of the use of pulverized fuel, we should continue to give serious attention to stoker problems; because many engineers are precluded from using pulverized fuel owing to the difficulty of installing electrostatic precipitators, and the still greater difficulty of disposing of large quantities of fine ash. So far as stoker units are concerned, further attention must undoubtedly be given to the questions of the grading of coals, removal of ash, and reduction of moisture content.

Many years ago I was associated with Mr. Harlow in his investigations on air-heaters, as a result of which re-circulation was adopted. It is interesting that Mr. Harlow now finds himself in difficulties with re-circulation, owing to the increase in temperatures and resultant increase in power consumption. It must not be overlooked that, notwithstanding the difficulties which have arisen owing to the increase in superheat temperatures, such as Mr. Harlow has indicated, a higher superheat temperature is still our goal, because that is the way to maximum efficiency.

Dr. A. Alan Taylor: The conclusions reached by Mr. Harlow in his paper would suggest the necessity of considerable modifications of our views with regard to power station design. I should therefore like to discuss the experiments to see if the conclusions are justified.

The conditions under which the tests were carried out were very different from those existing on full-scale plant. For example, the gases used for the tests were much cooler and probably contained a much higher proportion of air. The flue solids in the gas under test might be very different from those existing in a large boiler. Again, in a superheater the hot gas passes over cooled surfaces, whereas in these tests a cool gas was passed over heated surfaces. Further, the time of contact between the reactants and the catalytic surface may have been very different. It is quite possible that, at the gas velocity existing in a superheater, there is insufficient time or insufficient surface contact for these catalytic processes to take place to an extent sufficient to increase the dew-point.

With regard to the various catalysts, I would suggest that in

a superheater the catalytic effect of the deposit and not the iron-oxide scale would be the controlling feature, because in normal boiler practice the iron oxide is completely covered with a layer of deposit. Now from Figs. 5 and 6 it will be seen that, up to temperatures of about 1 100° F, there is nothing to choose between the catalytic effect of superheater scale from a stoker-fired boiler and the dust from a pulverized-fuel plant. At the same temperature they have almost exactly the same effect.

If a high dew-point is not obtained in pulverized-fuel plants, because the surfaces are coated with a dust which has only a small catalytic effect, then by the same reasoning a high dew-point should not be obtained in stoker-fired plant because the surfaces are coated with a deposit which has an equally small catalytic effect.

It is assumed throughout the paper that catalysis is the cause of the phenomena noted, but this is by no means proved and there are, in fact, several points which suggest that other factors may be playing an important part. I feel that this question should be placed beyond any doubt before we commit ourselves to the conclusions reached.

Finally, with regard to operating results on boiler plants, I have in mind one power station where the boiler arrangement is very similar to that shown in Fig. 7, and where the superheat temperature is 850° F, but in this instance, observations taken over a period of more than 4 000 hours have shown that it is always the air-heater over the primary superheater which chokes up. Again, high dew-points are occasionally found even where the superheat temperature is relatively low, and we can only conclude that in these cases at any rate, the high dew-points result from other causes.

Mr. G. Nonhebel: It seems to me to be important that an investigation should be made into the operating experience with gas- and oil-fired boilers. There must be boilers in the U.S.A. which use natural gas or oil for firing, and where the ash problem does not exist. It would be valuable from the point of view of Mr. Harlow's theory if it could be shown whether there is greater corrosion where there is a high superheat with an oil- or gas-fired boiler, making due allowance for the increased dew-point due to the water from the extra hydrogen in the gas.

I should like to support the suggestion that a radiant superheater is desirable for the final stage of superheating if Mr. Harlow's theory is correct. I have had experience of radiant superheaters with a powdered-fuel boiler of the Stirling type, where a brick baffle directly opposite the turbulent burners was replaced by a radiant superheater; the superheater stood up very well to those conditions and as the boiler was a powdered-fuel one there was no trouble from air-heater corrosion.

Mr. D. W. Lees: In their paper, Messrs. Rylands and Jenkinson state that bonded deposits occur only on stoker-fired boiler economizers and that practically no bonded deposits occur on economizers installed with pulverized-fuel-fired boilers. They also state, in the conclusions arrived at after carrying out their extensive survey of the chemical actions taking place during the formation of bonded deposits, that an important factor is the condition of the alumina in the fly ash, hydrated alumina giving rise to suitable conditions for the formation of bonded deposits. I assume, therefore, that any form of steam soot-blowing of boiler, superheater, economizer, etc., the water washing of superheaters as carried out in certain power stations, and the wetting of coal to promote better firing conditions on stoker-fired boilers, would tend toward hydration of the alumina in the fly ash. Conversely, any reduction in the quantity of moisture introduced would tend to improve matters as far as the dryness of the alumina is concerned. Obviously the moisture due to the combustion of hydrogen cannot be eliminated.

It would be interesting if the authors would give their views on this matter, having in mind the drying of pulverized fuel before firing, and if they would state whether in their opinion this pre-drying is a factor of much importance in the elimination of bonded deposits in pulverized-fuel-fired boiler economizers.

Referring to the prevention of bonded deposits on economizers of stoker-fired boilers, the authors state on page 86: "It may be that the processes involved in stoker firing can be modified in some way which will increase the proportion of spheroidalized fly-ash particles. . . ." It may here be of interest to refer to the greatly improved reduction of bonded deposits on the economizers and superheaters of two stoker-fired boilers at the Croydon power station, which have been fitted with air booster ducts under the stokers. The effect of this system of air distribution employing a zone of high temperature by means of an augmented air pressure, may actually simulate the conditions which obtain with pulverized-fuel firing, inasmuch as there exists a high temperature zone in the only position on the grate where any quantity of fly ash can be discharged into the gas stream.

Further, wetting of the coal previous to firing does not improve firing conditions, and is not resorted to, which is in favour of the point raised earlier in my remarks on introducing moisture to the flue gases. I believe through the good offices of the Boiler Availability Committee and the Fuel Efficiency Sub-Committee, that many power station engineers are conversant with this system of stoker firing, which is known as the Harper booster-duct system.

Mr. P. H. N. Ulander: I agree with Mr. Adams that the authors have singled out only two sets of conditions which could produce the effects they describe, whereas the problem is obviously a very complex one. For example, the reactions which occur in the combustion chamber and on the grate are not taken into account in their investigations.

Mr. Harlow mentions the following points which may cause trouble in connection with air-heaters: (1) High superheat and catalytic action, (2) leaky boiler tubes and economizer tubes, (3) low dew-point during soot blowing, (4) possible difficulties due to unsatisfactory combustion, and (5) the type of coal burned.

To these five I should like to add: (6) Low heating-surface temperature in air-heaters during starting up and shutting down, (7) low pre-preheating surface temperatures during periods of low boiler loads, (8) low dew-point during water lancing of superheaters and other surfaces, (9) localized low temperatures of the air-preheater heating surface due to the air for combustion reaching the forced-draught fan direct from the outside atmosphere through windows adjacent to the fans, or when the fans are placed in the basement with no provision for drawing hot air from the boiler house, (10) stoker rating, and (11) combustion chamber rating.

These are exceedingly complex questions. By far the greatest proportion of air-preheater troubles are due to low heating-surface temperatures. If it were possible to control the air-preheater temperatures or heating-surface temperatures so that they never fell below an empirically-established value, then most of the difficulties would be eliminated. In the U.S.A., automatic control of the coldest part of the heating surface has been introduced and has proved successful. Power-station engineers may be hampered at present by the lack of skilled and experienced labour—a factor which makes it more than ever desirable to introduce automatic temperature control.

Mr. L. C. Southcott: In Fig. 7 Mr. Harlow shows a boiler plant with a side-by-side superheater where extensive corrosion is reported in the air-heater behind the secondary superheater, the section behind the primary being comparatively undamaged. Severe corrosion also occurred on the external surface of the

superheater tubing, being most marked at the point of gas entry to the superheater and being mainly confined to that portion of the tubing facing the incoming gases. The tubes in the first row were thinned to about half their original thickness, leaving the external surfaces irregular due to localized attacks. Tubes across the whole width of the boiler were affected, and the replacement of many of them was necessary. Corrosion took place in the second row of tubes, but not to the same degree as the front row, while the rear row carrying the highest temperature steam (850° F) was not affected.

Fuels with a comparatively high sulphur content had been in use and the deposit on the external surface of the superheater was white in colour with underlying greenish sections. An analysis of the ash gave the following result:—

Silica (SiO_2)	16·20%
Iron oxide (Fe_2O_3)	13·68%
Alumina (Al_2O_3)	2·20%
Lime (CaO)	1·88%
Magnesia (MgO)	3·19%
Sulphates (SO_3)	38·81%
Sulphide (S)	Nil
Phosphates (P_2O_5)	1·75%
Chlorides (Cl_2)	Nil
Alkalis (Na_2O)	22·29% (by difference)

It would appear that sodium sulphate was mainly responsible for the attack. The degree of tube wastage was exceptional at this point, and it would therefore have been useful if Mr. Harlow had selected other installations to illustrate his theory. In view of the superheater corrosion being general across the width of the boiler, it might have been expected that air-heater corrosion would also be uniform.

Mr. D. Northall-Laurie: I have followed the two papers with great interest as I spent most of 1935 on a comprehensive research at two large power stations on the general question of reduction of the sulphur content of flue gases and, in particular, on the cause of the clogging of air-heaters and economizers by sticky deposits accompanied by corrosion, and, as a result of such research, I am able to suggest a remedy. The sticky dust showed the presence of acid sulphate of iron. Excessive moisture in the gases, caused either by burning too wet a coal or by steam leakage, was found to increase the trouble.

The solution of the problem appeared to resolve itself into the addition of an alkali to neutralize the acid as well as some control of humidity. It was not considered advisable to coat the walls of the air-heater passages with anything for fear of reducing the efficiency of the heat interchange, which had already been reduced by widening the spaces.

No reduction of this acidity was obtained by the addition of lime to the coal before burning unless excessive amounts were used, which was out of the question. Addition of an alkali to the flue gases was then tried. The most suitable and economical alkali to use was slaked lime dust, and an apparatus was set up to blow known amounts of dust into the boiler flue immediately above the economizer (Stirling boiler). Quantities of lime in amount equal to 3% of the coal burnt were blown in and no deposit collected in the air-heater. Some did collect on ledges and corners as a dry powder which gave an alkaline reaction when wetted. The quantity of lime used was reduced until the dust was still just alkaline. This occurred when about 0·2% was used; 0·06 was insufficient. The best moisture content of the flue gases was found to be about 1½ grammes of water per cu ft at n.t.p. The sulphur content of the coal being burnt at that time was 2%.

Several runs were made with this dosage and no sticky deposit was produced. Moreover, when the air-heater was opened for inspection it was found to be substantially clean and free from signs of corrosion. The "tell-tale" glass tube inserted in the flue at the base of the stack showed on some mornings a small amount of sticky deposit that had collected during the night shift owing to a deficiency of lime caused by stoppage or irregular working of the dosage plant.

The result of the work established the fact that clogging up of the air-heaters and the fins of economizers, with elimination of corrosion in all parts of the air-heaters, could be achieved by the simple expedient of blowing into the flue gases, at the correct spot, lime dust to an amount of about one-tenth of the sulphur content of the coal burnt with controlled humidity.

Mr. A. G. Forgan (*communicated*): On boilers where stages (*a*), (*b*) and (*c*) of Messrs. Rylands and Jenkinson's theory are present, and the inhibition of stages (*d*) and onwards can be shown, a guide to its correctness can be obtained. Flintshire pea slacks burnt under industrial plant boilers resulted in SO_2 and SO_3 formation causing severe local pitting. A smooth, thin bonded scale formed on the economizer, but in the course of normal working, it tended to crack allowing soot blowers to remove it. Similar thin hard deposits formed in the vertical tubular air-heater with downward gas flow. After 3 or 4 years' operation, a number of tubes choked at the bottom with deliquescent deposits, removable by water washing. Fig. 6 shows why excessive corrosion on these tubes was not experienced as compared with upward-gas-flow air-heaters. Drainage would carry weak solutions of SO_2 and SO_3 from hot upper to cooler outlet zones, thus avoiding increasing acid concentrations experienced with drainage from cold to hot zones. Completion of drainage and higher gas temperatures account for increased corrosion in the lower hot zones. Periodic soot blowing is beneficial, as it removes portions of weak acid solutions adsorbed on deposits.

These industrial boilers of 80 000 lb/hr m.c.r. operated under very different conditions from the boilers used in selected power stations. In normal operation they rarely exceeded 60 000 lb/hr. The grates were easily worked using a maximum of forced draught, thus reducing fly ash, whilst the combustion chamber was liberally designed allowing the flames to burn out some distance below the fire-row tubes. These two factors eliminate stage (*d*), and onwards. As, after a year's continuous working with little or no banking, only a thin bonded scale formed on economizer tubes, it is inferred that the authors' theory is correct.

A selected-station boiler of 100 000 lb/hr m.c.r. was operated at 65–70 000 lb/hr. Raising the output to 85–90 000 lb/hr was accompanied by choking of the fire-row tubes. Gun-type soot blowers had to be fitted. The increased boiler rating had reached the point where the fuel-burning equipment was overloaded. Reduction of boiler outage is bound up with the combustion arrangements. Heat released depends on furnace volume, but heat absorbed by water-tubes at a given combustion temperature depends on exposed tube area. As the size of boilers increases, heat release per unit volume should be decreased to maintain uniformity of flue-gas temperature leaving furnace on the different size boilers. The benefits of this practice would be felt throughout the steam generating unit, not only on the economizers, but also on the fire-row tubes, the superheater tubes and the air-heaters.

The immunity-period theory can be substantiated, as washing gilled economizer tubes results in lower draught losses than are obtained by rodding. The statement that soot blowers are not effective with bonded deposits holds true only where stalagmitic conditions develop. When no soot blowing was carried out on gilled-tube economizers, the bonded deposits were some 50% to 75% thicker, and the staggered tube gills formed dust traps which would have been absent had the tubes been in line.

Mr. H. Knott (*communicated*): The authors of the two papers may be interested in the following characteristics observed on a boiler of the industrial type. The boiler is one of a range of

six which are rated at 75 000 lb/hr, with a steam pressure of 350 lb/in^2 and a temperature of 700° F. The feed-water temperature of the economizer averages about 190° F at inlet and about 300° F at outlet. The gas-inlet temperature is about 600° F and the outlet temperature about 350° F.

These conditions are outside what the authors of both papers consider would give the bonded deposits. Nevertheless such deposits do occur, and the boiler has exhibited several of the phases described in the paper by Messrs. Rylands and Jenkinson. The boilers first went into operation about the beginning of 1938 and, due to war-time restrictions, only one or two boilers have been on the range at one time, which means that each boiler has had only about one-third of the operating hours it would normally have in a fully-loaded station. Until 1941, no cleaning of the economizer tubes, which are plain mild steel, had been found necessary other than regular soot blowing. During 1941, it began to be necessary to clean the economizer tubes by hand. A fairly adherent scale accumulated which could not be touched by soot blowing. From this time onwards it was found necessary to clean by hand after about 2 000 hours operating, by which time scale about $\frac{3}{8}$ in thick in places had accumulated. It has lately been found that this scale can satisfactorily be softened by water spray and finally washed off by hosing. According to Messrs. Rylands and Jenkinson, we should expect the boiler to exhibit a fresh immunity following the thorough washing. Insufficient time has elapsed for confirmation of this view.

Although the process appears to go in accordance with the description given by Messrs. Rylands and Jenkinson, there are two points in which the theories in neither of the papers fit the facts: (1) Tube-wall temperatures are low enough to be out of range of bonded deposits according to the theories of Rylands and Jenkinson, and (2) the superheat temperature is not high enough to cause extensive formation of sulphur trioxide in accordance with the theories put forward by Mr. Harlow.

Mr. G. H. Manning (*communicated*): These two papers are interesting in that both have suggested that the high dew-points observed in flue gases are due to the presence of a catalyst which acccelerates the formation of SO_3 from the SO_2 in flue gas. Mr. Harlow, indeed, has shown conclusively that rusty mild steel is an efficient catalyst for the reaction, and his results are in agreement with what we would expect from theoretical considerations.

The reactions involved in the deposition of a sulphuric-acid film from a flue gas are

(1) $SO_2 + \frac{1}{2}O_2 = SO_3$—Slow reaction, except above about 1 000° C.

(2) $SO_3 + H_2O = H_2SO_4$ (gas)—Fast reaction.

(3) H_2SO_4 (gas) + xH_2O (gas) = $H_2SO_4 . xH_2O$ (liquid).—Fast reaction.

Equilibrium conversions for reactions 1 and 2 are shown in Figs. A and B. These are calculated from the corresponding equilibrium constants.*† The temperature at which reaction 3 begins, i.e. the dew-point, and the concentration of acid deposited at this temperature can be obtained from the results of Johnstone‡ and Taylor.§

In practice equilibrium is, of course, not attained, the formation of H_2SO_4 being governed by the progress of reaction (1). In the absence of a catalyst, the actual conversion of SO_2 to SO_3 in a flue gas will be small (½–1%), since at the temperatures at

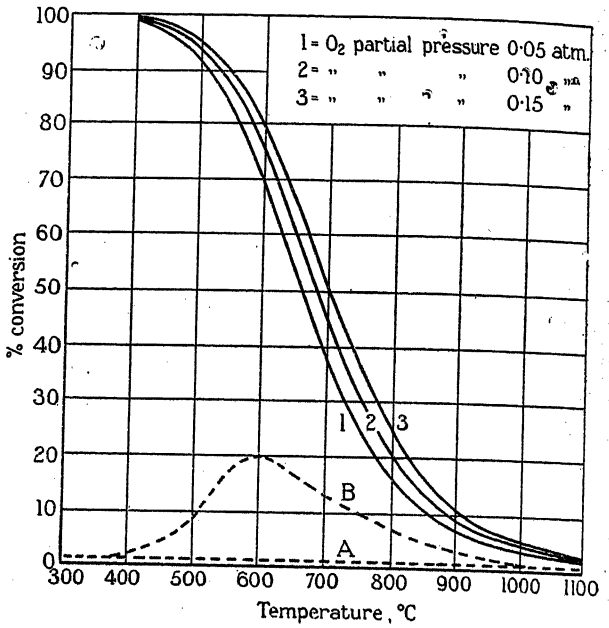


Fig. A

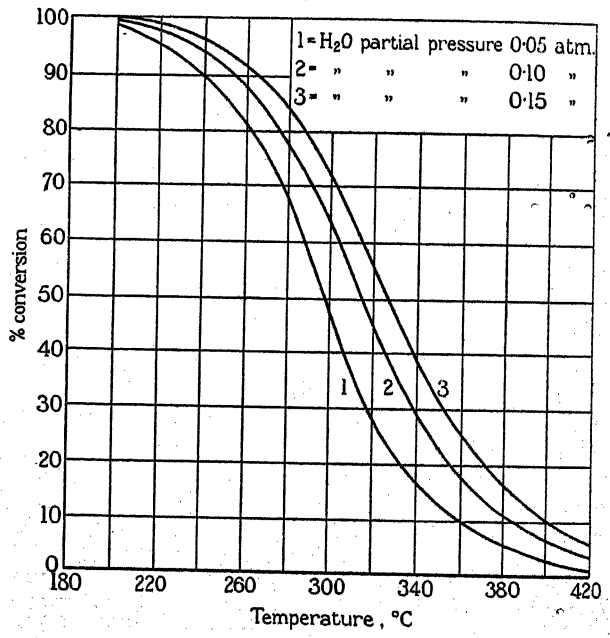


Fig. B

which reaction is rapid, the equilibrium conversion is small. This corresponds to A of Fig. A. If, however, the flue gas meets a catalyst on its passage to the chimney the reaction rate will be increased at lower temperatures, and since the equilibrium conversion is high at lower temperatures, the actual conversion will be increased. Experience of the contact process for the manufacture of sulphuric acid* shows that catalysts, such as Fe_2O_3, usually have little catalytic effect at temperatures below 400° C and maximum effect at about 600° C. The effect of such catalysts on the formation of SO_3 at different temperatures could thus be represented qualitatively by B of Fig. A.

It can be seen that Mr. Harlow's results are in excellent agreement with the qualitative theory outlined above, and I consider that he has proved his point.

The formation of sulphuric acid in a flue gas is also explained

* M. Bodenstein and W. Pohl: *Zeitschrift für Elektrochemie*, 1905, 11, p. 373.
† M. Bodenstein and M. Katayama: *Zeitschrift für physikalische Chemie*, 1909, 69, p. 26.
‡ H. F. Johnstone: 1929, University of Illinois Engineering Experiment Station Circular No. 20.
§ A. A. Taylor: *Journal of the Institute of Fuel*, 1942, 16, p. 25.

* F. D. Miles: "Manufacture of Sulphuric Acid (Contact Process)," 1925, p. 90, (Gurney and Jackson).

by Messrs. Rylands and Jenkinson on the basis of a catalytic theory. I should like to make the following comments on this paper:

(*a*) It is unlikely that ferric sulphate at the surface of economizer tubes would be at a high enough temperature to have an appreciable catalytic effect on the formation of SO_3.

(*b*) The authors assume that aluminium sulphate deposited when a sulphuric acid solution is concentrated, will be in a hydrated form. They show no experimental evidence, however, that the solid phase in equilibrium with sulphuric acid solutions of aluminium sulphate is hydrated $Al_2(SO_4)_3$. The results of Dobbin and Thomas* suggest that the solid phase in equilibrium with a saturated solution of $Al_2(SO_4)_3$ in 10% H_2SO_4 is the anhydrous salt at 50° C. In the absence of evidence to the contrary, therefore, we would expect the solid phase under the conditions on economizer tubes to be the anhydrous salt.

As it stands, therefore, the explanation offered by Rylands and Jenkinson for bonded-scale formation appears to be based upon dubious evidence.

Mr. J. E. O'Breen (*communicated*): I should be obliged if Mr. Harlow could give some information about one point, not mentioned in the papers, and which was not brought up at the verbal discussion. Has he examined whether the dust concentration in the flue gases or the size of the dust has any influence on the actual dew formation and the resulting deposits on economizer and air-heater surfaces?

It is often said that fog and mist form more easily when the air contains large quantities of dust and smoke; if this is true, then it also seems likely that the formation of dew from SO_3 is speeded up by dust in the flue gases. If the dust could be removed from the gases at a point where the temperature was still above the dew-point, then a condition of over-saturation without actual dew formation might occur when the temperature dropped below dew-point, and the bad effect might be reduced. In any case the removal of the larger dust particles, say those of 40 microns and more (flue dust in stoker-fired boilers is nearly all of this size) would considerably reduce the formation of bonded deposit. On page 86 Messrs Rylands and Jenkinson say, referring to the 8 stages in which deposits are found to take place, that "if any of these stages can be inhibited, the subsequent stages can be prevented from occurring." Removal of the dust or part of it will at least reduce the effect of stages (*d*), (*e*), (*f*), (*g*) and (*h*), and I am of the opinion that for this reason it should be recommended.

The general design of the majority of types of dust collectors used in power stations in this country is such that they are not suitable for installation before the economizer or air-heater. In America a tubular dust collector has been developed in recent years which is very suitable, owing to the size and shape of the inlet and outlet connections, for installation before the economizer or air-heater, and it is now being made in this country. Unless the investigation carried out by the authors leads to methods of operation whereby the heating surfaces are kept clean under all conditions, it seems advisable to give serious consideration to the installation of dust collectors before the economizer, or in any case before the air-heater, instead of after the heat-absorbing surfaces, which at the present time seems to be their most favoured position.

Mr. C. S. T. Paul (*communicated*): Both papers refer to a catalytic action as being responsible for the conversion of the SO_2 in the gases to SO_3: and Mr. Harlow suggests that the scale on the superheater tubes is the catalytic agent.

There are several stoker-fired boilers having superheat temperatures of 800–850° F, with which no trouble due to high dew-point is experienced, and in view of the fact that the same high superheater temperatures also exist in boilers which are pulverized-fuel or oil fired, I do not think that it is correct to draw the conclusion that the high superheat temperature and scale are solely the causes of the trouble. Furthermore, one of the worst cases on record for trouble of this nature is a chain-grate stoker-fired installation in which the superheat temperature is only 750–780° F. I think that the factor primarily responsible for the SO_2–SO_3 conversion is the nature of the grit obtained from thin fuel beds with a high velocity of air through the fuel bed. As one speaker explained, by spraying the coal with milk of lime or powdered lime to counteract the catalytic action of the grit, the rate of production of SO_3 can be appreciably reduced. However, I understand that this practice has not been continued at the station at which it was first applied.

That the rate of production of SO_3 has been found to be dependent on the rate of firing, i.e. a combination of draught, stoker speed, and fuel-bed thickness, indicates that it may be the method and degree of combustion which is primarily responsible for the particular nature of the grit in acting as a catalyst. One difference between stoker firing and pulverized-fuel firing is the method of introducing the preheated air into the furnace. For stoker-fired units, would it not be better to reduce the velocity of air through the incandescent section of the fuel bed, and apply highly-preheated secondary air over the rear of the stoker, the allocation of the total air being approximately 50%, say, at 600°–700° F above and 50% below the grate at the more usual air temperature of 260–300° F?

Since the attainment of a high cycle efficiency by means of high pressures and temperatures is in practice only worth while when accompanied by regenerative feed heating, it is little short of ridiculous to propose the elimination of the air-preheater, as has been suggested in some quarters.

It is significant that in SO_2 waste-heat boilers one of the methods adopted to avoid corrosion is to use tubes with extended heating surface of cast iron to enable the heat from the gases to be extracted rapidly.

The use of cast iron for the elements of air-preheaters does not appear to have been so widely used in power stations as it might be, having regard to its adoption in other industries for much the same purpose.

Mr. H. E. Wallsom (*communicated*): Whether the two papers have common connection, namely the dew-point of the gases, is a subject for controversy, but there can be no doubt whatever that they are in agreement in tracing the common origin of deposits both in economizers and preheaters to sulphuric acid.

It is not clear from their paper whether Messrs. Rylands and Jenkinson consider it essential (1) that before these deposits can accumulate, ferric sulphate must first be formed on the metal surfaces by the attack of sulphuric acid, or (2) that the aluminium sulphate is formed only on the economizer. Both these assumptions are incorrect, for if a water-cooled glass surface is inserted into the gas stream before the economizer for only a few minutes, an appreciable amount of water-soluble aluminium salts and, to a lesser extent, iron salts is deposited.

Many experiments have confirmed Mr. Harlow's statement that, except in some special circumstances, the greater proportion of the sulphuric acid is formed in the passage of the gases through the superheater. From the boiler outlet to the stack there is in general a reduction in the percentage of sulphuric acid in the gases; a reduction much greater than can be accounted for by the deposition on economizers and pre-heaters.

A recent experiment with water-cooled glass surfaces at the outlet of boilers equipped with two-pass, horizontal, inter-deck superheaters fully confirmed Mr. Harlow's views; in every case up to three times as much acid and sulphates were deposited on the tubes opposite to the hotter sides of the superheaters.

Mr. E. Watkinson (*communicated*): At least one assumption is

* J.T. Dobbin and L. C. Thomas: *Journal of Physical Chemistry*, 1937, 41, p. 655.

common to the two papers, namely that SO_3 is responsible for the beginning of the trouble. It is also generally agreed that trouble from bonded deposits and high-temperature dew-points has materially increased in recent years. Running parallel with this condition is the fact that both superheat temperatures and the amount of bare water walling has also increased. Can it be that an excess of water wall is responsible for reducing the temperature of the combustion chamber adjacent to the walls, to such an extent that it is possible for SO_3 to exist in the actual combustion chamber? If there is anything in this theory, then one would expect boilers with narrow combustion chambers and a large amount of water wall to give more trouble than wide combustion chambers and a small extent of water wall.

The authors all agree that pulverized-fuel-fired boilers are practically immune from these troubles; is not this owing to the fact that under these conditions of firing turbulence is created in the combustion chamber? By this means the products of combustion are thoroughly mixed and therefore at a uniform temperature throughout. This fact would ensure the absence of SO_3 in the combustion chamber except in minute quantities, and thus account for the general immunity of pulverized-fuel-fired boilers from high dew-points.

If it could be established that turbulence was essential in the combustion chamber, one might achieve this result in the case of stoker-fired boilers by introducing above the fire approximately 25% of the total air supply, preheated to a relatively high temperature. To obtain this high preheat a secondary air-heater would have to be installed before the economizer, in addition to the usual primary air-heater following the economizer. The introduction of this highly-preheated air would shorten the flame produced, and eliminate the danger of delayed combustion around the superheater tubes. If the scale formed on the superheater tubes is detrimental because of its catalytic properties, this is another reason why scaling should be avoided if at all possible. In this respect it would probably be beneficial to have large superheaters situated farther away from the combustion chamber.

There seems little doubt from the large amount of attention being given to this important problem that the quantity of bonded deposit and the high dew-point will gradually be reduced and probably eliminated. It must be remembered, however, that whilst there is sulphur in coal we shall always have to guard against low dew-points, and in this respect it would appear that cast-iron air-heaters will prove the solution.

THE AUTHORS' REPLIES TO THE DISCUSSION AT THE JOINT MEETING OF THE INSTITUTION WITH THE INSTITUTION OF MECHANICAL ENGINEERS

Messrs. J. R. Rylands and **J. R. Jenkinson** (*in reply*): We agree with Mr. Adams that the larger problem of boiler availability and of bonded deposits in general is complex; our contribution relates only to the problem of bonded deposits in economizers, but the same method of approach may also prove useful in dealing with the complexities of the larger problem.

Mr. Adams regards the authors' proposed preventive measures as being somewhat impracticable. But measures similar to those suggested have actually been used for some time. Given suitable design of equipment the practical difficulties largely disappear. Closely-pitched circular tubes, whether gilled or plain, are always a source of difficulty if deposit growth has been allowed to continue, but modern designs with fewer tubes and shallower tiers present fewer problems.

In mentioning increased ratings, and especially increased rates of combustion per square foot of grate area, Mr. Adams touches upon an important aspect of the whole problem of boiler availability. Research into these aspects of boiler design and operation will undoubtedly throw a much-needed light on the source of many fouling troubles.

This line of investigation was also mentioned by Mr. Shakeshaft. If the SO_3 formed during combustion could be reduced to SO_2, so that the gases leaving the combustion chamber were free from SO_3, the length of the "immunity period" could be expected to increase, perhaps indefinitely. We do not deny the possibility of the formation of SO_3 elsewhere in the boiler, but we suggest that all such reactions may depend in the first instance on traces of sulphate deposit. It appears that fine dust forms hard deposits more readily than the coarser particles. The artificial deposits that we produced were made from dusts of less than 60 microns, the finest dust giving the hardest and strongest deposits. We suggest that the elimination of the finer dusts from stoker firing would be a step in the right direction, and, as a corollary, we regard coal ash with a very high fusion point as possibly having undesirable features.

We are in full agreement with Mr. Fosbrooke's contention that increased boiler outage may entirely offset high thermal efficiency. On the other hand, we think it will eventually be possible to design stoker-fired equipment on such lines that many of its disadvantages will be overcome.

In reply to Mr. Rees's comments, we would emphasize that our paper relates to hard bonded deposits on economizers, and that the reactions described appear to occur almost exclusively in the limited economizer-surface temperature range as found in "power-station practice." We agree that artificial deposits having an *appearance* similar to those found in practice can be built up by methods other than those described, but we suggest that *hard bonded deposits* cannot be formed by, for example, "thermal precipitation" or by "aerodynamic effects" alone.

Again, we agree that some or all of the existing theories criticized by us may fit the facts in other parts of the boiler plant; we believe that the "fused ash" theory explains much of the phenomenon of "bird-nesting" and that the "dew-point" theory is important in the explanation of air-heater corrosion and fouling, also that the "sodium salt" theory may throw light on certain boiler and superheater deposits, but we insist that the aluminium-sulphate reactions are of dominant importance in the surface temperature range of approximately 250–500° F. Apparently the only type of reaction known to be common throughout the boiler plant is that involving SO_3 and the formation of iron sulphate in a greater or lesser degree, and the various secondary reactions resulting therefrom.

Mr. Jeffrey's question as to the applicability of our findings to superheater tubes has, to some extent, been answered above. The method of approach to the problem is certainly capable of extension to superheaters, and has the advantage of eliminating apparently insuperable complexities. Superheater-surface temperatures appear to be too high for the occurrence of reactions closely similar to those in the economizer, although Barkley* mentions that water vapour and SO_3 can exist in combination, even at 620° C. This possibly explains the existence of some of the iron sulphate on superheater tubes.

Mr. Lees suggests that moisture in the gases may influence the state of hydration of the alumina, and this may be a factor in the bonding of deposits. We doubt this influence of flue-gas moisture; the degree of hydration of the alumina particles seems to be largely a matter of their temperature, and to be independent of the original moisture content of the fuel, whether fired on

* J. F. Barkley: Bureau of Mines Technical Papers, No. 436, 1928.

stokers or in the pulverized form. We suggest that the experiences at Croydon are more likely to be related to the greater proportion of fused fly-ash particles than to the moisture in the fuel.

On the other hand, extra moisture in the gases may well result in troubles in the air-heater, where actual condensation may take place on the metal surfaces. This point was emphasized by Mr. Ulander. In some cases leakages from expanded economizer-tube joints have caused serious air-heater corrosion and blockage.

We were interested to learn that Mr. Northall Laurie had successfully applied lime dust in an endeavour to reduce corrosion, more particularly in the cooler portions of the boiler plant. The use of lime along with the fuel is unlikely to be successful; the high temperatures in the combustion chamber probably prevent the formation of calcium sulphate. In fact fuels high in calcium content have been known to cause hard calcium deposits in the boiler passes.

We welcome Mr. Forgan's comments in support of our views, in particular his practical experience of early washing of heating surfaces; we agree that availability is associated with combustion ratings. Mr. Knott's experiences confirm our statement that no tube form confers immunity from bonded deposits where conditions are otherwise favourable. The successive stages described by Mr. Knott conform well with the general theory. Regarding the temperature range, reference to Fig. 12 will show that a bonded deposit containing a fairly large amount of iron sulphate, together with some aluminium sulphate, may be expected to form in the surface temperature range 190–300° F. Such a deposit would usually prove quite amenable to water washing.

Mr. O'Breen suggests that good results might follow from the removal from the gas stream of particles larger than, say, 40 microns. It is not unlikely that much smaller particles contribute largely to bonded-deposit formation.

In reply to Mr. Manning, we would point out that we have not concerned ourselves primarily with high dew-points, and that in fact economizer deposits may form when the dew-point is quite low. Regarding comment (*a*), Section 2.5 refers clearly to the occurrence of sulphuric acid on *tube surfaces*, and we would point out that Mr. Manning's suggestion is contrary to the findings of other workers. It is possible that he is thinking in terms of the catalysis of solids, whereas the theory we offer involves catalysis in solution.

Comment (*b*) is not in accordance with the latest knowledge on the subject. There *is* experimental evidence that aluminium sulphate *in acid solution* is hydrated. The solubility curve, part of which is given in Fig. 5, should make this clear. The cycle described indicates that the hydrated sulphate, on being thrown out of solution, is immediately dehydrated in the high-temperature gas stream, passing through the glutinous stage in the process. The question is, therefore, not whether the aluminium sulphate in the solid phase in equilibrium with sulphuric acid is hydrated, but whether the solid separating from sulphuric acid is the hydrate. On this point there is excellent independent evidence, apart from the visual evidence afforded by our experiments in building up artificial deposits.

We do not disparage the work of Dobbin and Thomas, but it should be known that the paper cited by Mr. Manning deals with $Na_2SO_4 . Al_2(SO_4)_3 . 14H_2O$ and not with $Al_2(SO_4)_3 . 18H_2O$. Prof. Partington has stated that if alumina is dissolved in hot concentrated sulphuric acid, the liquid on cooling slowly deposits an indistinctly-crystalline mass of aluminium sulphate $Al_2(SO_4)_3 . 18H_2O$. This statement is based on experiments by Wirth in 1913: while Smith* in 1942 gives the composition as $Al_2(SO_4)_3 . 17H_2O$. The agreement between Smith and Wirth affords independent evidence that the solid separating from concentrated sulphuric acid is the hydrate; in view of this evidence, we consider that Mr. Manning's final paragraph is not in accordance with the facts.

* *Journal of the American Chemical Society*, 1942, 64, p. 41.

In reply to Mr. Paul, we agree that the more extensive use of cast-iron in air preheaters would probably reduce deposit troubles in that part of the steam-generating plant. As with the economizer, the problem is one of design and arrangement, and since cast-iron air-heaters are usually more expensive and occupy more space than the conventional type, it may be some time before boiler designers and plant users accustom themselves to such a development.

Mr. Wallsom's experiment with a water-cooled glass probe does not necessarily indicate that the sulphates form in the gas stream. The fact that the probe *was* water-cooled makes it reasonable to suppose that a film of acid solution would form almost at once. Such a film would dissolve minute particles of dust, forming iron and aluminium sulphates.

In regard to Mr. Watkinson's query on the effect of turbulence, we hesitate to express a definite opinion. We imagine that the influence of water-wall surface on the reaction

$$\frac{[SO_2]^2\,[O_2]}{[SO_3]_2} = K$$

would depend on a time factor, and the gas velocities may be such that equilibrium is never attained. The use of secondary air in the way suggested has been the subject of experiment, but as far as we are aware, no conclusive results have yet been obtained.

Mr. Harlow (*in reply*):* Having regard to the divergence of opinion which existed on this problem and considering that the explanation proposed appears to be new, it is gratifying to find such a wide measure of support from those in responsible control of boiler plants.

With regard to Mr. Adams's suggestion of the possibilities of acid production in much larger quantities in ways other than the passage of gases through the superheater, I can assure him that in some boilers at least the acid deposition obtained at the boiler outlet is as heavy as at any other point in the gas system, indicating that the gases *can* acquire all their undesirable properties in this respect before they leave the boiler.

In my view, there is no doubt that the radiant-heat superheater, as suggested by Mr. Fosbrooke for the final superheating of the steam, would eliminate all but a negligible degree of catalytic effect; but, as he will appreciate, this type of superheater has its own problems—not the least of which is the difficulty of maintaining the metal at a temperature within safe limits during low-load periods when the radiant heat from the furnace is much higher proportionately than the steam flow. This may not be serious in base-load stations if means are adopted for circulating steam through the superheater during starting-up periods. The matter, however, is really one for manufacturers who specialize in this type of equipment, particularly the question of the availability of suitable steels.

Mr. Fosbrooke's suggestion of an independently-fired superheater burning pulverized fuel is possibly another way of overcoming the difficulty, subject, of course, to the complications to which he refers. I cannot say whether an oil-fired unit would be free from high-dew-point trouble, as no investigations have yet been made with the gases from this type of plant, but at present I see no reason to suppose that this would be the case.

The foregoing suggestions, however, would not help to relieve existing plants, many of which are having their efficiency and availability seriously impaired through high dew-point

* This is an abstract of Mr. Harlow's reply, which will be published in full in the *Proceedings* of The Institution of Mechanical Engineers.

conditions, and the suggestion of spraying the catalytic surfaces with an anti-catalytic agent or "poison" is put forward for what it is worth as a possible solution to this difficult problem. As Mr. Fosbrooke points out, the surfaces must of necessity be scavenged by soot blowers at frequent intervals, and for this reason it was suggested that the anti-catalyst be applied by them, since if the blowers are capable of reaching the whole of the superheater surface for cleaning purposes, they are equally capable of contaminating it to the same extent with any material which the steam can be made to carry.

It is well known that catalysts are extremely susceptible to "poisons" even in minute amounts, but whether the inhibitive effect of lime and pulverized-fuel dust, as shown by the experiments, is due to "poisoning" of the catalyst or whether this merely results from the formation of an impervious coating which prevents diffusion of the gases to the oxide surface, is not yet clear. In any case, a comparatively thin coating appears sufficient to stop the action. Experiments are proceeding on determining the minimum coating of lime or pulverized-fuel ash which will immunize the surfaces sufficiently to be of practical value in preventing trouble.

It is interesting to note that Mr. Thornton and Mr. Manning have actually measured the surface temperature of their superheater tubes. I think it will be agreed, however, that the figures given would not necessarily hold good for all superheaters, and that in tubes which were, to any appreciable extent, coated by internal deposits, or starved of steam, the surface temperatures would be very much higher. For these reasons, amongst others, the actual steam temperature is not always a correct indication of the maximum surface temperature of the tubes. Where superheat tube failures are frequent, it is evident that the tubes must often attain a temperature very much higher than 50–80° F above that of the steam. Where flame impingememt takes place, the temperature of the oxide is very problematical and it is obvious that local temperatures may be set up which differ greatly from those deduced from the steam temperature.

Mr. Rees considers there are other possible methods of sulphuric-acid formation and implies that its origination in the fuel bed or combustion chamber must not be discounted. This view has been widely held despite surprisingly little evidence to support it. Many investigations have been made by my company of both SO_3 content and dew-point conditions throughout modern boiler units, and in no case has any extremely high dew-point been found in a furnace outlet or combustion chamber. It is true that some slight elevation has been noticed in the former, but this could be explained by the catalytic action of the furnace walls.

I do not claim that my conclusions have any bearing on the superheater trouble to which Mr. Jeffreys refers, which I believe to be due to independent causes, since superheater deposits are encountered with and without high-dew-point troubles.

It is not clear why Mr. Ross considers it unfortunate for the boiler makers that he cannot find any arguments against the technical evidence submitted in the paper, particularly as the results of the investigations show that the responsibility for this trouble rests largely with the nature of the fuel. For a given boiler the amount of acid formed will depend on the amount of sulphur fed to the furnace, and if this can be reduced the acid formation and dew-point will be proportionately lowered. It is to be hoped that coal research will result in a considerable reduction in the sulphur content of the fuels supplied to power stations.

Dr. Taylor disparages my conclusions on many grounds, most of his criticisms being unfortunately based on false assumptions. He suggests that in the experiments the gases were very much cooler, contained much more air and different flue solids from those on a large-scale plant, and that the time of contact between gas and catalyst was much greater than in practice. Actually the condition of the gases was closely comparable to that in actual practice, while with regard to the time of contact Dr. Taylor appears to have overlooked the fact that, although the velocity of the gas was somewhat lower, its length of path over the catalyst was correspondingly less than in practice, and when this is taken into account the contact period is almost identical with that of the gases in the superheater of a modern boiler. This was intentionally arranged.

He also suggests that the refractory scale is really the important catalyst, as the iron oxide is normally covered by deposit. If this were correct only heavily-coated tubes would produce high dew-points, since the external scale only acquires catalytic properties at temperatures 200–300° F higher than the oxide, and a considerable thickness would be necessary to raise the surface temperature by this amount. Lightly-encrusted tubes, therefore, would be unaffected. In practice this is not the case, since boilers often develop high dew-point troubles immediately or soon after they are put back into service following cleaning. Whatever the mechanism operating, the fact remains that the scale appears to permit catalysis to take place, whereas a coating of pulverized-fuel dust, which differs both physically and chemically from the scale, greatly hinders the action.

Dr. Taylor claims knowledge of a boiler similar to that shown in Fig. 7 in which the air-heater is affected in the opposite manner. In this case the unit must obviously be unsymmetrical in some feature of design or operation to account for only one of the air-heaters choking, so that it is not suitable for judging this question as the effect of the differential superheat on the air-heater may be masked by other opposing factors.

In Mr. Northall-Laurie's experiments in neutralizing the acidity of the flue gases by the continuous injection of powdered lime it is surprising that such a relatively small proportion was effective. This method, however, aims at counteracting the effect of the oxidation of the SO_2 rather than removing the cause, which is the object of the proposals I have put forward.

Replying to Mr. O'Breen, I do not think the separation of dust from the gases would greatly reduce their tendency to condense their acid content, since dew-point temperatures measured on filtered gas samples check quite well with those determined on the dust-laden gases. Although the use of a dust filter before the air heater would, of course, reduce the solids deposited in the air heater, the acid would still form with the resultant corrosion effects.

Much has been said about the complexity of this problem, but in my view it presents no exception to the rule that occurrences which at first appear to have an abstruse and complex explanation are often proved capable of a comparatively simple one. The chemical and physical changes which take place in the different parts of the boiler system as a result of reactions between the sulphuric acid and the many constituents of coal ash, at the various temperatures which prevail, may be complex and numerous, but the important fact—the reason for the acid formation—is not difficult to understand.

It has often been suggested that in order to avoid these dew-point troubles the air-heater be eliminated and the final heat extraction from the gases be left to the economizer, notwithstanding the increased stack loss which would be incurred. In fact, this was the trend in American design some years ago. This readiness to sacrifice heat to the stack gases, however, is in strange contrast to the general reluctance to forgo the advantages of increased steam temperatures.

Even if the elimination of the air-heater would remove the difficulty, which is by no means certain since the economizer may also be affected, the problem would still resolve itself into a choice between rejecting heat to the stack or to the cooling tower.

A RECENT DEVELOPMENT IN SQUIRREL-CAGE INDUCTION-MOTOR STARTERS*

By G. A. WAUCHOPE, Associate Member.†

(*The paper was first received 5th June, and in revised form 8th October*, 1943.)

SUMMARY

The paper describes a design of star-delta starter for squirrel-cage motors, the application of which enables this type of machine to be used in many fields where a slip-ring motor has formerly been essential.

The investigations which prompted the development of this starter and the subsequent tests and deductions are discussed, with particular reference to centrifugal and similar forms of pumps.

(1) INTRODUCTION

In the course of investigating difficulties which were being experienced with the starting of electrically-driven pumping machinery, the author found it necessary to examine in some detail the electrical and hydraulic phenomena which occur during the starting of centrifugal and kindred pumps.

In a pumping station in which were installed a number of pumping units automatically started and stopped by changes in water-level, the motors were of the 3-phase double-wound squirrel-cage-rotor type controlled by contactor-type star-delta starters. It was found that the current during the starting period was higher than had at first been anticipated, with the result that the overload releases in the starters had to be provided with special restraining devices to prevent tripping under normal conditions of starting. It was further observed that the high current-peak occurred when the motor connections were automatically changed from star to delta. This phenomenon was found in installations where the motors were of the simple squirrel-cage type as well as where the rotors were of special design to limit the starting current.

Consideration showed that such phenomena must take place for the following reasons:—

When an electric motor is directly coupled to a centrifugal, turbine or axial-flow pump and is in the process of being started up, the total torque developed by the motor consists of:—

(*a*) Torque to produce the pressure, etc., of the fluid contained within the pump.

(*b*) Torque to overcome bearing and gland friction, etc.

(*c*) Torque absorbed in windage losses in the motor, etc.

(*d*) Torque to accelerate the rotating masses of the pump and motor.

The speed of the motor increases until, if permitted to do so, it will reach a stable speed when star connected. This is the speed at which the total torque is absorbed by load and losses so that no accelerating torque is available. At this point the supply is disconnected from the motor.

It is necessary that a reasonable length of time be permitted to elapse before the motor is reconnected to the supply, so as to avoid short-circuiting the supply through arcs formed at the point where the connections are broken. During this time the only energy available to prevent the set coming to rest is the kinetic energy of the rotating parts. In most cases it will be found that the rate of absorption of this energy by the pump, and to some extent by the windage losses of the motor, is very rapid, so that during the interval when no electrical energy is being supplied to the motor the speed falls rapidly.

When the delta connection is made the motor is switched-on at a much lower speed than that at which it was disconnected, and consequently in accordance with its characteristics the current taken is high. The torque developed is now considerably in excess of that prevailing when the connections were broken, so that rapid acceleration follows. In most cases this torque is the highest that can be imposed on the mechanical parts of the machine, and the current is also the highest that will be taken from the line.

Fig. 1 shows the characteristics of a standard squirrel-cage

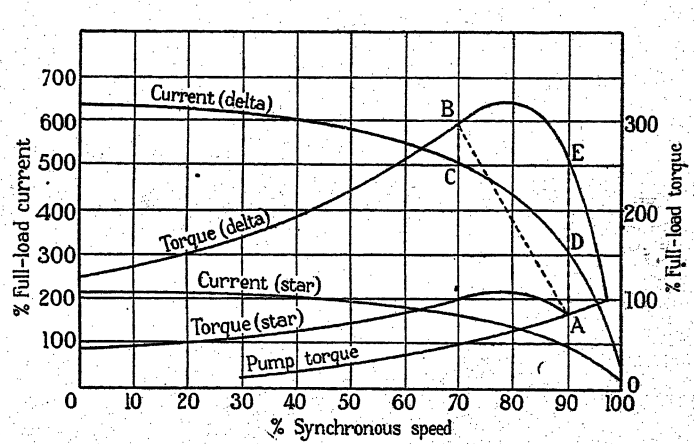


Fig. 1.—Current/speed and torque/speed curves for standard squirrel-cage motor driving centrifugal pump.

motor coupled to a centrifugal pump in which practically all the pressure generated by the pump is dissipated in overcoming hydraulic friction in the piping. It will be seen that when connected in star the speed of the set will increase until it reaches a point where the pump torque coincides with the motor torque (A), the pump torque including the friction of the pump, bearings and glands as well as that absorbed by the hydraulic operation of its rotating parts.

During the time when the electric supply is disconnected the speed falls from that at A to that at B, and when reconnected the motor will take the current indicated at C, the corresponding torque being shown at B. Had it been possible to change from star to delta instantaneously the current would have risen only to that at D and the torque to that at E.

For the reasons given above, it will be appreciated that the shorter the time interval in changing from star to delta the less the current peak and the torque; but also, on account of the transient effect, the greater the likelihood of the delta-current peak being high. This transient effect is due to the fact that the magnetic field of the motor does not collapse immediately, a residual voltage persisting in the stator winding which produces a large flow of current when connected to the supply if, as must frequently occur, the connection is made when the residual voltage is out of phase with the supply voltage.*

* Installations Section paper.

† Gwynnes Pumps, Ltd.

* *Journal I.E.E.*, 1943, 90, Part II, pp. 147 and 149.

(2) EFFECT OF HYDRAULIC CONDITIONS ON STARTING TORQUE

(2.1) Conditions under which Pump Operates

The starting torque of centrifugal and other velocity pumps may vary widely with the conditions under which the pump is operating, which may be as follows:—

(*a*) With the discharge valve closed until the pump has attained its full speed, after which it is opened and the fluid allowed to flow.

(*b*) With an automatic non-return, flap or reflux valve which opens when the pump generates a greater pressure than that due to the fluid standing in the discharge pipe. Here the torque characteristic will be similar to that with a closed discharge valve, until fluid begins to flow when the torque will increase rapidly.

(*c*) In the case of a circulating system where all the head generated is absorbed in hydraulic-pipe friction and similar losses which are approximately proportional to the square of the rate of flow.

(*d*) If the discharge piping is empty and is only filled up with fluid during the starting period.

(2.2) Starting-Torque Characteristics of Centrifugal Pumps

The values vary somewhat with the design of pump but the curve is more or less of the same shape for all pumps of this class.

Fig. 2 illustrates the above conditions as applied to a normal

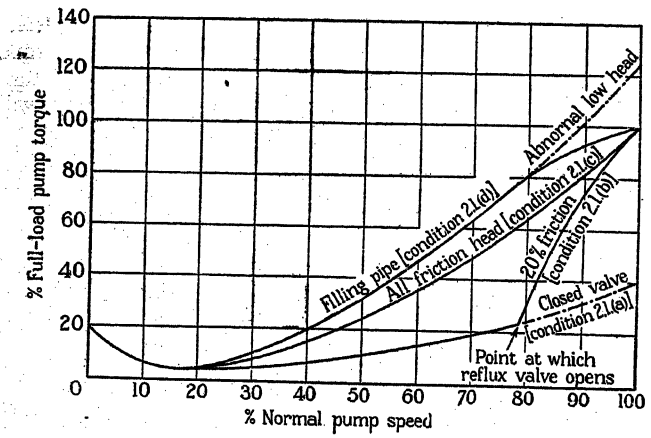


Fig. 2.—Torque/speed curves for typical centrifugal pumps under three conditions of pumping.

form of centrifugal or multi-stage pressure pump, from which it will be seen that with star-delta starting the last-mentioned condition—of filling the discharge pipe—is the most onerous, while if the discharge valve is not opened until the pump has attained its full speed the motor may reach a high speed in star connection before being changed to delta.

In the type of pump discussed the h.p. absorbed when running at a constant speed is a minimum with a closed discharge valve and increases as the flow increases, but not necessarily according to any simple law.

(2.3) Starting-Torque Characteristics of Axial-Flow and Mixed-Flow or Screw Pumps

In axial-flow pumps the h.p. is much higher when the discharge valve is closed than when discharging under its most efficient working condition. This h.p. may be of the order of twice the power absorbed under maximum-efficiency conditions. It will therefore be appreciated that difficulties arise in attempting to start a pump of this description against a closed valve.

The axial-flow pump, which is often used for land drainage or irrigation, is frequently of the vertical-spindle type with a non-return valve. Therefore it has to generate sufficient pressure to raise the water-level to a fair height before the valve opens and any appreciable discharge takes place. Fig. 3 illustrates such a

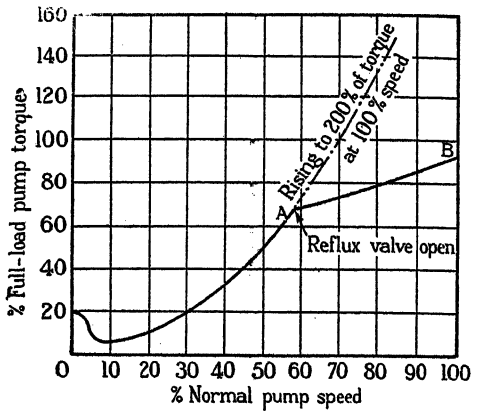


Fig. 3.—Torque/speed curve for axial-flow pump.

characteristic curve. It will be appreciated that the torque rises rapidly to point A, after which the water flows and the torque increases more slowly to point B. The chain-dotted extension of the curve shows the torque which would obtain if the valve remained closed.

Mixed-flow or screw pumps are somewhat of a compromise between the centrifugal and the axial-flow types, and consequently their starting-torque characteristics are intermediate. The power absorbed by the pump at closed valve may be approximately the same or slightly more than the normal power at the maximum efficiency of the pump.

(2.4) Slowing-Down between Star and Delta

Fig. 4 shows how rapidly the speed of a pump falls after switching off. These curves were prepared from calculated figures, and the time of coming to rest added from actual observation of a 6in double-inlet split-casing centrifugal pump driven by a 15 h.p. 6-pole squirrel-cage induction motor.

Curve A indicates the conditions when operating with the discharge valve closed [Section 2.1(*a*)]. Curve B shows the condition where the whole of the pressure generated is absorbed in friction and similar losses [Section 2.1(*c*)]. In this particular case it is observed that if the motor attains 83% of synchronous

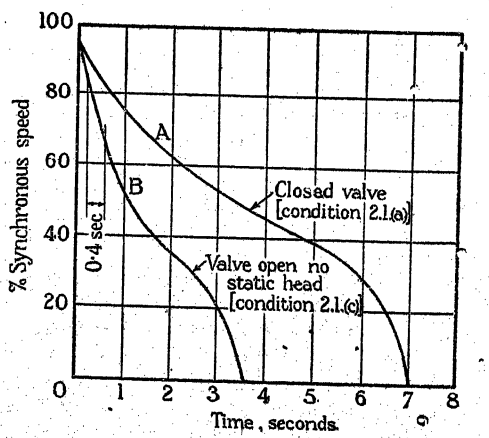


Fig. 4.—Fall-of-speed/time curves for 6-in centrifugal pump and motor.

speed in star, and if the interval between breaking the star connection and making the delta connection is 0·4 sec, the speed will have dropped to 65% of synchronous speed.

Similar conditions apply to all combinations of pumps and motors, but it will be appreciated that since the power absorbed by a particular pump is roughly proportional to the cube of its speed, whereas the stored kinetic energy is only proportional to the square of the speed, a greater slowing-up effect will be experienced with higher-speed pumps and therefore the greater will be the current peak when the delta connection is made.

(3) CONCLUSIONS FROM PRELIMINARY INVESTIGATIONS

When starting a motor that drives a machine in which the torque developed is absorbed partly in acceleration and partly in some other form of work, it is evident that slowing down must take place if the supply of electrical energy is temporarily cut off, and that the current taken when reconnection is made must depend upon the extent to which the speed is reduced. This effect is pronounced in the star-delta starting of motors driving centrifugal and axial-flow pumps and fans, where this form of starting is frequently employed. The current peak may be considerably enhanced by transient effects due to residual voltage persisting in the stator winding which may be out of phase with the supply when the delta connection is made.

It will be seen that if the time during which the supply is interrupted is comparatively long, the current at reconnection will be high owing to the reduced speed of the motor; on the other hand, if the time of interruption is short the transient currents may be higher, but of course their value is erratic as it depends upon the residual voltage and its phase relationship to the supply. Furthermore the time cannot be reduced below a certain limit without the risk of short-circuiting the line connections in the switch.

Similar conditions occur with auto-transformer starting, the slowing down occurring during the transition period. This does not apply to the Korndorfer auto-transformer starter, in which part of the transformer winding is used as a choke to maintain a limited supply of energy to the motor during this period.

(4) MODIFIED FORM OF STAR-DELTA STARTER

(4.1) Starting Sequence

A starting sequence has been developed by the author in which the connections can be changed from star to delta without a break in the supply to the motor and without the voltage across the windings being diminished below the star voltage. By this means current peaks are minimized and the usual transient effects are eliminated.

Fig. 5 shows the four starting steps, the current taken from the line, and the current in the windings. It will be seen that the sequence is as follows:—

Step 1—The motor is connected in star in the ordinary manner and the machine permitted to run until a steady speed has been reached.

Step 2—A resistor is connected in parallel with each of the motor windings. The current from the line is increased by the amount passed by these resistors but the current in the windings remains unaltered. The duration of this step can be as short as mechanically possible as there is no change in the running conditions of the motor during this period.

Step 3—The star point is now opened in such a manner that the motor windings are in delta but have a resistance in series with each phase. This results in an increased voltage across the windings. The dip in the current curve is due to an alteration in the voltage phase-angle when the connections are changed from star to delta. It only occurs for a fraction of a second and does not appreciably affect the torque. This reduction in current is finite and is not a transient. Acceleration then takes place to a higher steady speed with corresponding decrease in current.

Step 4—The three resistors are short-circuited so that the motor windings are now connected in delta. The voltage on the windings is increased to full line value, the current rises, and further acceleration takes place with decreasing current until the machine attains its final steady speed.

Fig. 6 is a schematic diagram of the connections described above.

(4.2) Starting Resistances

The values of the resistances influence the starting-current peaks in the following manner:—

Step 2—The current passed by the resistors which are connected across the line added, with due regard to power factor, to the motor current represents the peak current on Step 2.

Step 3—The same value of resistance must be considered as being in series with the windings which are connected in delta; consequently the current taken from the line at the commencement of this step is dependent to some extent on this value.

Step 4—The voltage across the windings is now increased by the drop in potential across the resistors which was obtaining before the latter were short-circuited, and the current rise is therefore again dependent upon the values of the resistances.

The resistances selected for a motor and starter may be determined by finding the most onerous conditions of starting torque which are likely to be experienced and adjusting the values so that the peak current on Step 2 is equal to that on Step 4, which will consequently provide the lowest maximum peak over the starting condition.

Where the load is relatively light such as in starting unloaded machine-tools or other plant where the torque is chiefly absorbed in the acceleration of moving parts, the motor runs up to a fairly high speed in star with consequent low current, and a high value of resistance can be selected so that the current on Step 2 is no greater than the initial switching-on current of Step 1. Step-3 peak will probably be no greater than Step-2 peak, and

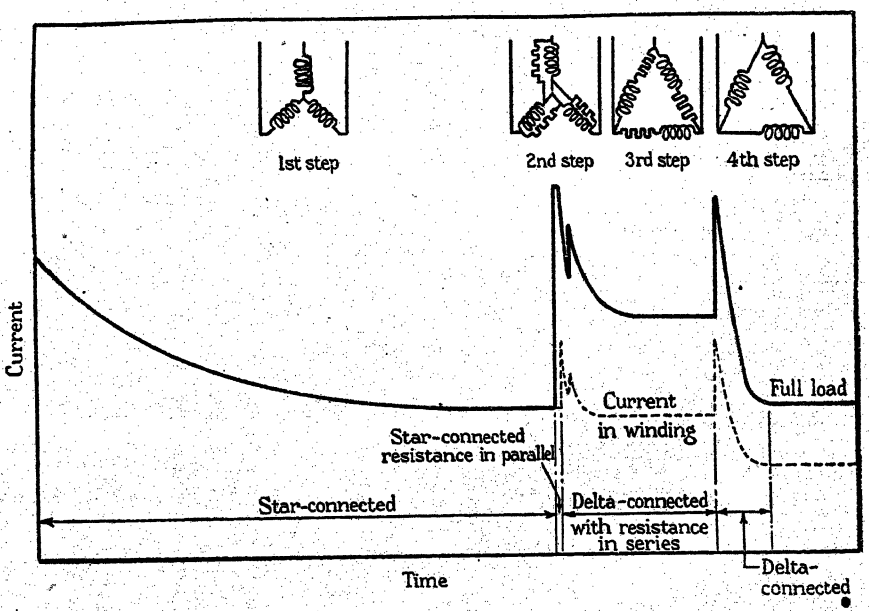
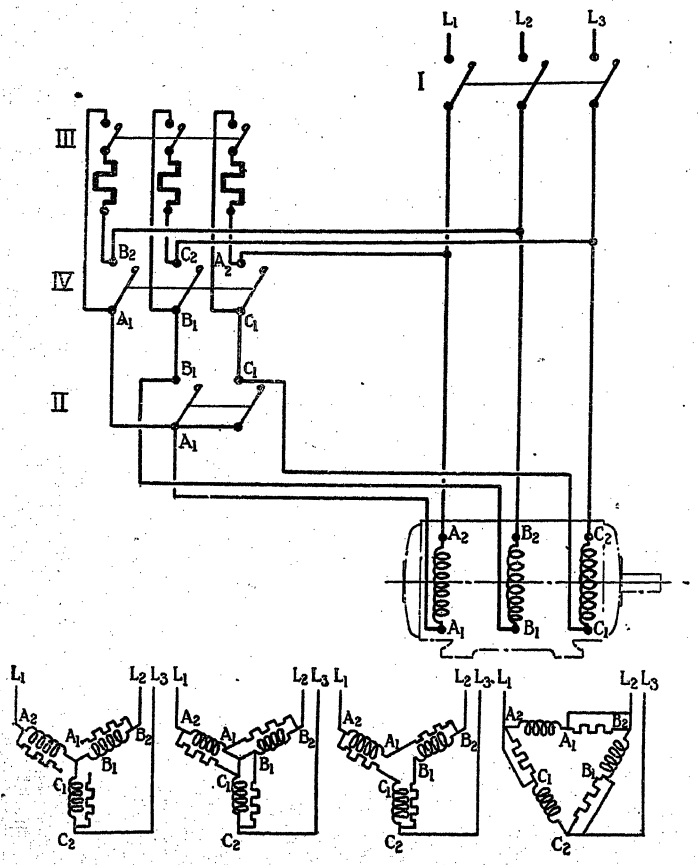


Fig. 5.—Starting sequence of modified star-delta starter.



Step 1	Step 2	Step 3	Step 4
I & II Close	III Closes	II Opens	IV Closes
Star	Winding in star Resistance in star	Delta with resistance in series with winding	Delta

Fig. 6.—Continuous-torque star-delta starter.

Step-4 peak will consequently be quite low since the change in voltage when the resistance is short-circuited will be quite small owing to the low load-current.

It will be seen that the higher the resistance the lower peaks 2 and 3 but the higher peak 4, and vice versa. That the value of these resistances is not critical will be observed from test results described later.

(5) DESCRIPTION OF TESTS AND DEDUCTIONS

(5.1) Motor Driving a Centrifugal Pump

Comparative tests have been carried out on a 15-h.p. squirrel-cage motor driving a centrifugal pump and started by means of a normal contactor star-delta starter and by the modified starter.

The oscillograms taken are shown in Fig. 7(*a*) with normal star-delta starting, and 7(*b*) with the modified form of starter.* Fig. 7(*a*) shows the manner in which the current falls to zero during change-over and then rises to a high value when the delta connections are made.

The pump was arranged to draw water from a tank and discharge it back into the same tank, the rate of flow being controlled by a sluice valve in the discharge pipe. The effect of working with a partially-closed discharge valve is to create an artificial head which is equivalent to the presence in the system of frictional losses such as would be experienced in a pipe-line or through condensers, etc., and it will be remembered that the power absorbed by a centrifugal pump running at a constant speed is reduced as the head is increased. It is therefore possible by this arrangement to simulate various hydraulic-load conditions by altering the sluice valve opening.

The oscillograms in Fig. 7 show the performance with the two types of starter and were taken when the sluice valve was adjusted so that the power absorbed by the motor when it attained full speed was approximately its full rated load; consequently they indicate similar conditions to those shown on the curve in Fig. 2 marked "All Friction Head [Condition 2.1(*c*)]." This corresponds to an onerous condition of starting which is usually encountered only in circulating systems where there is no static lift of the fluid.

The oscillograms shown in Fig. 8 were taken when the pump was started up in a primed condition but with the discharge valve closed.

Here it will be observed that with the normal starter the peak current is still high at change-over, but that with the modified starter it never rises above the switching-on current in star; in fact, the final peak caused by Step 4 is not discernible. This condition is frequently met with in practice, and the maximum peak does not exceed 190% of full-load current.

Fig. 9 shows the current plotted on a time-base during the starting-up of a centrifugal pump with the valve fully open and without static head. The dotted line shows the performance with a normal star-delta starter and the full line the operation with the modified starter.

Fig. 10 shows the speed and torque curves with the two forms of starter operating under these conditions.

It should be noted that with the normal starter, after change-over—during which the torque has fallen to zero—the torque suddenly increases to a high value, whereas in the modified starter the increments of torque are relatively gentle.

(5.2) Motor Driving Unloaded Machine-Tool

Where the motor is driving an unloaded machine-tool or similar plant involving gearing with a certain amount of backlash this effect is even more marked. It will be appreciated that many machines are driven by motors which never have to exert more than full-load torque when running at full speed, but that with star-delta starting the torque may rise to 2½ times full-load torque or more in the form of a quick take-up of backlash, and that this condition represents the highest stresses which at any time are imposed on the gearing, etc.

It therefore seems reasonable to assume that the cost of maintenance of such machines can be reduced by employing a starter in which the torque is limited to smaller values and the mechanical shocks are eliminated. The lower the load on the motor at starting the more gentle are the increments of torque in the case of the modified starter.

(5.3) Variation of Starting Resistance

Tests were carried out to enable comparisons to be made with different values of resistance. Fig. 11 shows the results of these tests with 5, 6·25 and 7·5 ohms per phase respectively, and indicates that with a high resistance the second peak is reduced at the expense of the higher third peak but that with a low resistance the second peak is much higher than the third peak.

It is observed that, in general, the peaks at Steps 2 and 3 are so close together owing to the short time-interval, that for practical purposes they may be considered as one, and for clarity the momentary dip has not been shown.

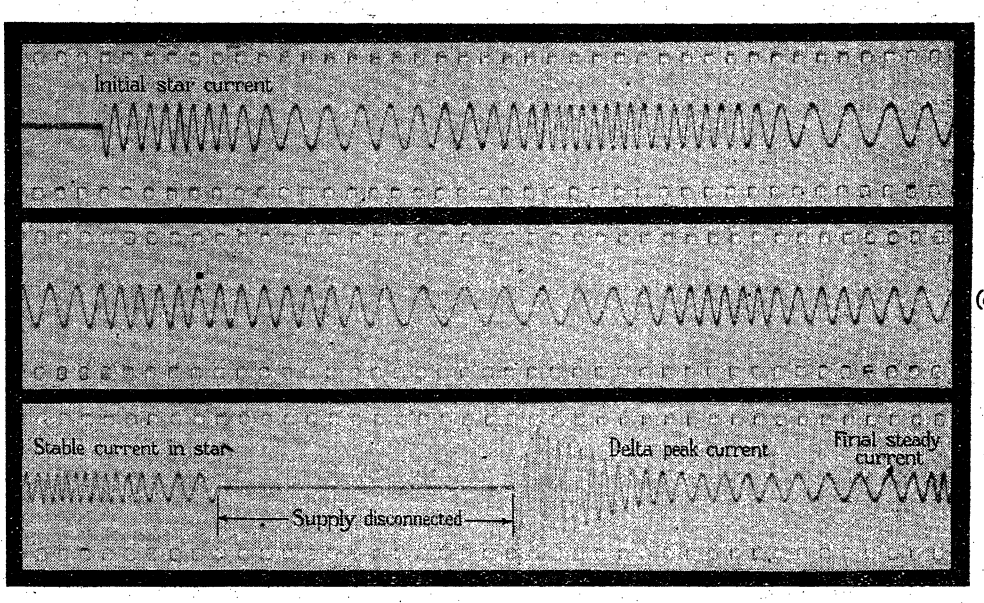
* Apparent irregularities of the time-base on the oscillograms are due to unevenness of the drive consequent upon the very low speed at which the oscillograph was run in order to save film. These do not affect the results.

(6) OTHER METHODS OF STARTING SQUIRREL-CAGE MOTORS

The following is a brief outline of the usual methods of starting squirrel-cage motors:—

(6.1) Direct Connection to Line

Squirrel-cage induction motors may be started by switching direct to line, in which case the normal current may be six or more times the full-load current. This peak may, however, be considerably reduced by employing high-resistance or high-reactance squirrel-cage windings, or by various ingenious forms of double-wound squirrel-cage rotors which, while limiting the starting current, maintain a reasonably high torque. But these features usually involve a lower efficiency and frequently a lower power factor than those obtained with a normal form of rotor, and it is rare that the starting current is much less than four times the full-load current. Such a high peak may be objectionable to the electricity supply authorities.



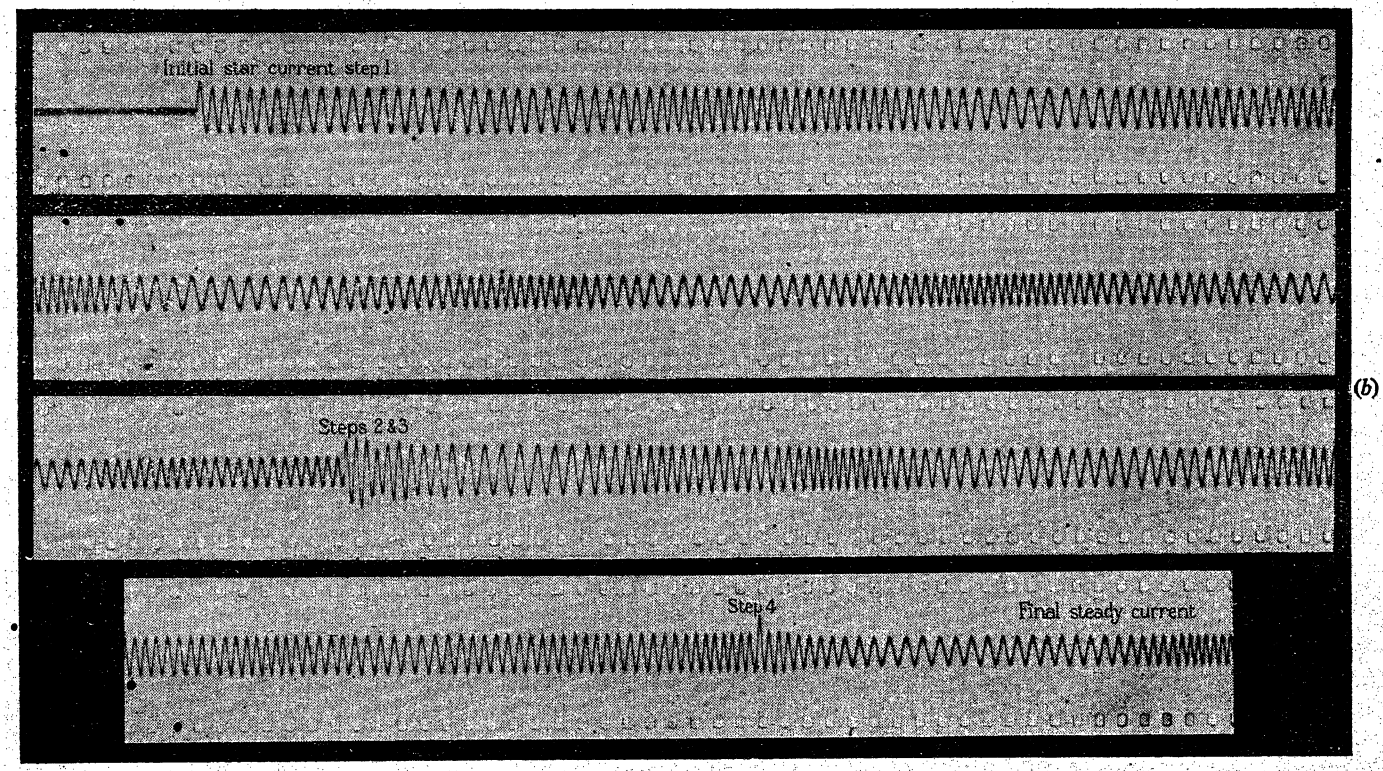


Fig. 7.—Starting current of 15-b.h.p. motor driving a centrifugal pump. Valve full open, no static head. Line current at 50 c/s, 400 volts.
(*a*) With standard starter. (*b*) With modified starter. Resistance in starter 6½ ohms.

(6.2) Auto-Transformer Starters

With auto-transformer starters the initial peak current may be reduced, but this has the effect of increasing the second peak which can be quite high owing to the slowing down of the driven machine in the manner described in Section 2.4.

With the Korndorfer auto-transformer starter a continuous torque is applied, although in many cases when the transformer is operating as a reactance during the transition period the torque is somewhat reduced. This design, however, does eliminate the transient effects.

(6.3) Star-Delta Starting with Sectionalized Stator Windings

The effect of slowing-down has been recognized amongst continental manufacturers, and, although the author is unaware

of actual instances, he understands that equipment has been designed in which the stator winding is divided into two or more sections; first all sections are connected in star, and then each section in turn is reconnected in delta.

(6.4) Stator-Resistance Starting

Stator-resistance starting is sometimes employed, but this has the disadvantage of limiting the starting torque of the motor to a marked extent.

(7) APPLICATION OF SQUIRREL-CAGE MOTORS WITH MODIFIED STAR-DELTA STARTERS

(7.1) Types of Load

The modified starter is suitable for drives in which the torque developed by the motor when star connected is ample to accelerate the driven machine, as is the case with centrifugal pumps and fans, and in many instances with axial-flow pumps and fans. It is also suitable for starting unloaded machine-tools in which the frictional torque is less than the torque developed by the motor in star, the acceleration taking place smoothly and without shock to the

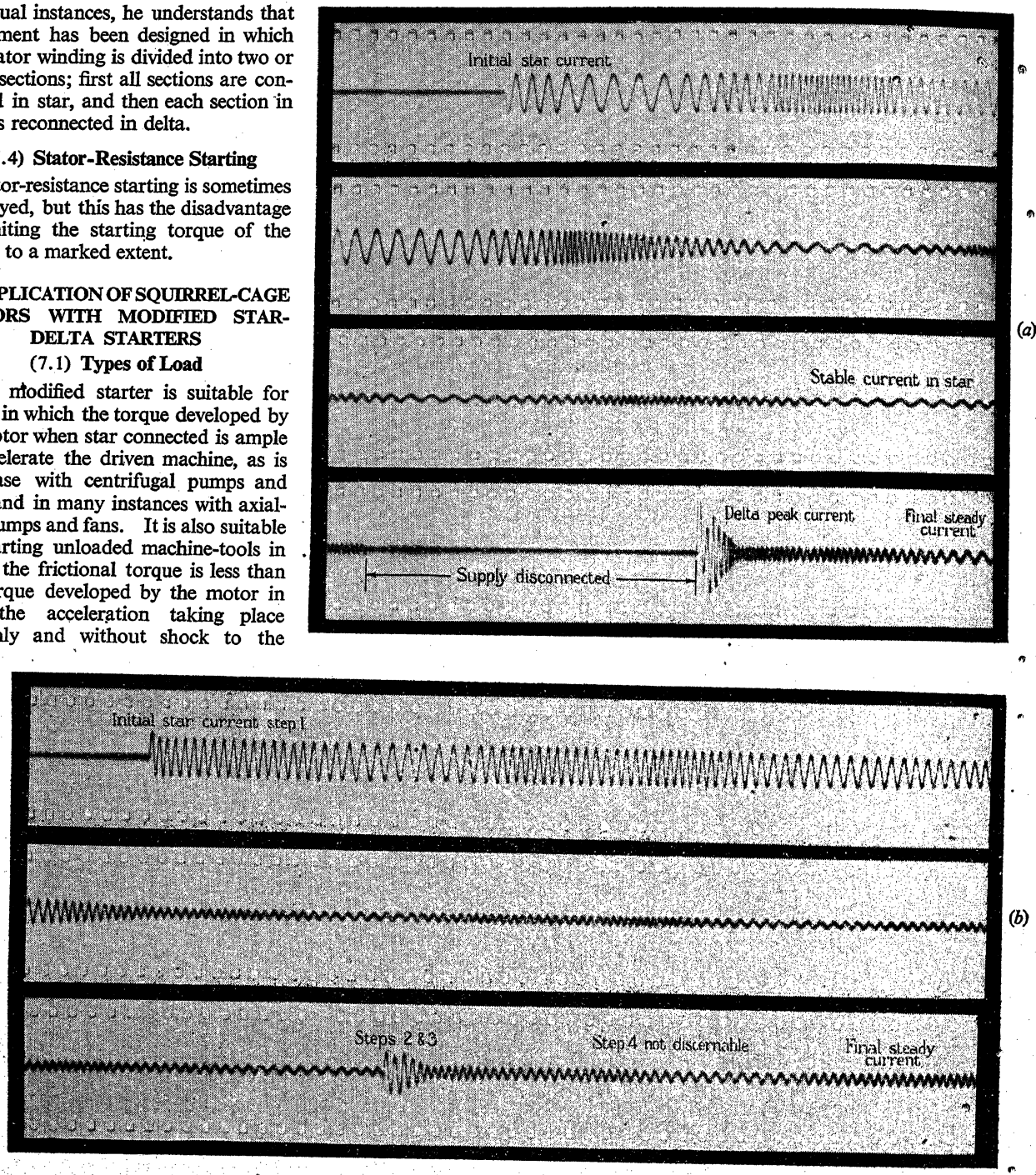


Fig. 8.—Starting current of 15-b.h.p. motor driving a centrifugal pump. Valve closed, no static head.
(*a*) With standard starter. (*b*) With modified starter. Resistance in starter 6½ ohms.

gearing, etc., and the current peaks during starting not exceeding the first switching-on current where the load torque is relatively light—such as 20% to 30% of full-load torque—with consequent reduction in wear and tear of the mechanical parts.

(7.2) Type of Motor

The most suitable type of motor to employ with the modified starter is one in which the starting torque is maintained at a high value during the acceleration period in star, this corresponding to a normal squirrel-cage motor in which the star-switching-on current may be twice full-load current, the peak current on the remaining steps being limited to, say, 2·5–2·7 times full-load current with a centrifugal-pump load.

(7.3) Effect on Line Voltage

From the supply authorities' point of view the modified starter has the advantage that the increments of current taken from the line may be limited to twice full-load on switching-on and two

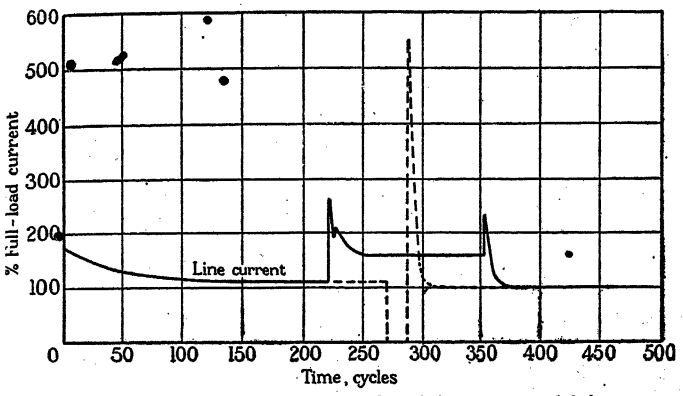


Fig. 9.—Starting-current/time curve of 15-b.h.p. motor driving centrifugal pump. Valve full open, no static head.

——— Modified starter.
- - - - Standard starter.

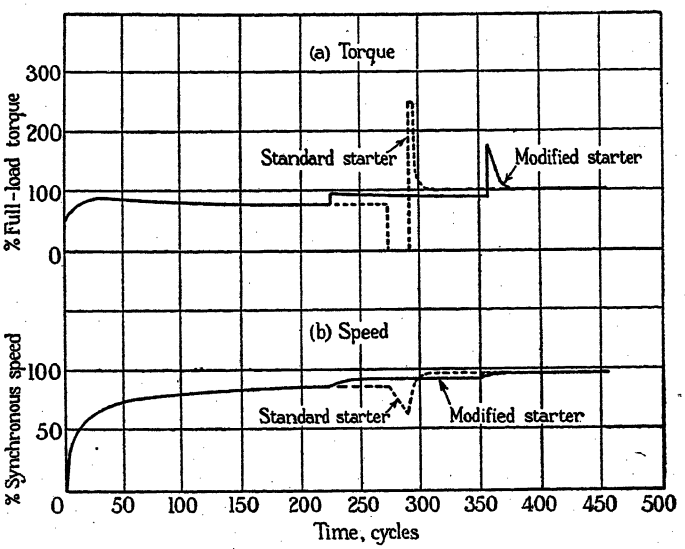


Fig. 10.—Torque and speed curves for 15-b.h.p. squirrel-cage motor driving centrifugal pump. Valve full open, no static head.

further increments of about half full-load, whereas with the normal star-delta starter the current increment may be also twice full-load on the first step but 5–6 times full-load on the second step.

Voltage fluctuations on the supply mains during starting will be considerably reduced, owing not only to the limitation of the peaks of current but also to the absence of the interruption of the load on the mains during change-over.

(8) CONCLUSIONS

It is well known that the squirrel-cage motor is more robust than the slip-ring type and that its first cost is much lower. In many cases, however, the slip-ring type has been employed in order to restrict the peak starting-current to values which will not cause undue fluctuations in the supply voltage. In other cases consideration of mechanical shock during starting, low efficiency, or low power factor has made it necessary to use the slip-ring type notwithstanding its disadvantages, which include wear of slip-rings, maintenance of brushes, etc.

It is hoped that by the use of the modified form of star-delta starter described in this paper the highly efficient squirrel-cage motor with its high power factor and robust construction can be employed in many cases where hitherto slip-ring motors or squirrel-cage motors with rotors specially designed to give low starting currents have had to be used.

These advantages are achieved by the use of a starter which may use standard parts throughout and is no more complex than the normal slip-ring motor starter.

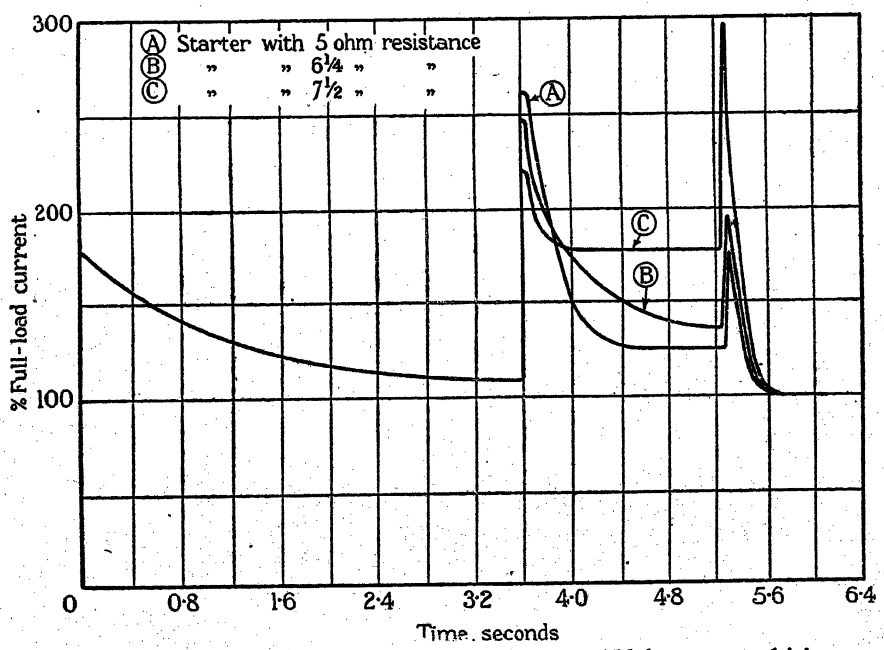


Fig. 11.—Current peaks with various values of resistance. 15-b.h.p. motor driving centrifugal pump. Valve full open, no static head.

(9) ACKNOWLEDGMENT

The author is indebted to Messrs. Allen West and Co., Ltd., and to Messrs. Gwynnes Pumps, Ltd., for help in obtaining much of the information contained in this paper, and also to Mr. H. Brooke and Mr. J. J. Fisher for their kind assistance in the carrying out and interpretation of the investigations.

MAINTENANCE OF DISTRIBUTION PLANT AND MAINS ON A.C. NETWORKS*

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SUMMARY

The importance of efficient maintenance of all plant for electricity distribution is paramount, for upon this depends its satisfactory performance and immunity from failure within itself.

In this paper the authors discuss the influence of design and layout of plant and mains on the maintenance programme, as viewed by the distribution engineer.

The experience of several London undertakings having underground cable systems for transmission and distribution at voltages of 66 kV to 0·4 kV forms the basis of this paper.

INTRODUCTION

The frequency with which apparatus should be examined, and the time to be allocated for each overhaul, are dependent on (*a*) the design of the individual unit with regard to its electrical duties and the atmospheric conditions under which it has to operate; (*b*) the electrical and mechanical strength of the materials employed; (*c*) the accessibility of the parts requiring normal inspection and testing; and (*d*) the physical layout and housing of the units, together with facilities for carrying out routine maintenance on site. The closest co-operation between the designer and the maintenance engineer is at all times desirable, in order that those details in design which require excessive maintenance may be suitably modified.

It is the function of a maintenance engineer to organize the necessary maintenance, examination and testing of all sections of plant under his control, so that the plant may carry out its functional operation successfully, and incipient faults be found and eradicated before they lead to failure on line.

(1) STAFFING

In normal times maintenance staffs are most economically employed on distribution networks if both capital and revenue work is carried out by the same staff. While it may be possible to find continuous employment for a purely maintenance staff this does not usually apply to new construction. It is also an advantage if the engineering staff responsible for maintenance of plant are in addition responsible for its installation, so that their previous experience may be most usefully applied, and they will have complete knowledge of all plant from its inception.

The high standard of technical knowledge required by specialized engineering and testing staffs in connection with modern networks calls for a combination of training at engineering colleges and practical ability; regarding the latter, the authors consider that works experience in a manufacturing company should be gained by an engineer before he joins a supply undertaking.

Similar remarks regarding works training also apply to the manual staff of fitters; not only, however, is engineering ability to be considered, but reliability and conscientiousness are essential, for on large networks it is not generally possible to afford continual supervision on site. The fitter should be trained to call the attention of senior staff to anything abnormal, however minor, that may arise during normal maintenance work.

Regarding jointers other than for specialized jointing required on cables of 33 kV and above, the best results are obtained if they are trained by the undertaking concerned. In this way apart from receiving training in the undertaking's own methods, they acquire invaluable local knowledge.

With a centrally sited department carrying out maintenance of plant on a network of distributing stations and transformer chambers, the staffing and operating arrangements permitting the utilization of maintenance man-hours on site to the maximum are of great importance and require careful consideration, such arrangements being dependent on local conditions and the size of the area which is covered. A successful scheme, adopted by a London bulk supply undertaking, employs operating engineers in the department responsible for maintenance of plant in distributing stations throughout a large area, one engineer being always on duty at a central locality. They are mobile and are "authorized persons," i.e. persons qualified to operate particular switchgear and plant under the undertaking's control. In times of emergency and system disturbance, they co-operate with the central control department in going to site to assist in the restoration of supply and the general operation of the switchgear as required by the emergency. Apart from other duties, they carry out isolation and earthing of equipments for normal overhaul, and testing and re-commissioning of equipments when work is complete. Fitters report direct to site.

Distribution standby maintenance staff for a network supplied by a London undertaking is covered by a "night control" outside normal working hours. This consists of 4–5 engineers, drawn from district engineering staffs and centrally sited, each of whom has local knowledge of at least two districts. Manual staff, normally engaged in routine maintenance, is sited at main district substations and is available in any emergency. This night control centre is supplied with operational key maps, together with information, brought up to date daily, of all switching, and alterations to position of links in disconnecting boxes, etc.

A further system is that operated by an undertaking with an area of supply ranging from inner London through suburbs to rural districts. Operation of switchgear controlling all mains and transformers down to 11/2-kV substations is under the direct supervision of a centrally-sited system control engineer and his staff. The system is divided into three sections, namely 66 kV to 22 kV inclusive, 11 kV, and less than 11 kV, each section being responsible for all mains and substations falling within the defined voltage segregation as regards both construction and maintenance, and carrying the necessary staff of engineers, fitters, jointers, etc. Engineers of each section are always available, but maintenance work, with the exception of emergency repair work, is carried out during normal working hours.

(2) SAFETY PRECAUTIONS

The authors stress the great importance which must be attached to the strict observance of safety regulations. Many undertakings have adopted the "permit-to-work" card system. In this system, before work is commenced on any high-voltage plant, a "permit-to-work" card is issued to the competent person in charge of such work by an "authorized person" who has carried out the operation of making the apparatus safe by isolating and earthing. It is signed by both parties at the time of issue, and space is provided on it to designate the equipment

* Transmission Section paper. † London Power Co., Ltd.
‡ County of London Electric Supply Co., Ltd.

nd that part of it on which it is safe to work, together with a ırther space stating where the earth connection has been made. This card is held by the competent person in charge while such ork is in progress, and when work is completed his signature added and the card is then returned to the authorized person, ho cancels it by the addition of his signature. In systems emloying a central control for system operating, the particulars of is card are given to the control engineer at the time of issue nd of cancellation, and no plant is made alive until the permit ard has been cancelled.

It is important that the section of the plant on which the work authorized should be clearly and precisely specified. All live arts of apparatus must be locked off, and only authorized ersons allowed access to keys. Fitters should be forbidden to y-pass any lock by undoing bolts or fixings, or to commence ork on apparatus until a permit card has been issued to them nd the apparatus proved dead by an authorized person.

The use of master keys for operating locks on high-voltage pparatus should be forbidden. The use of one key for one ock is an extra safety precaution in minimizing operating misakes. In earthing high-voltage circuits supplying feeders, ansformers, etc., the earth connection should first be made rough an automatic oil circuit-breaker where possible. The se of detectors during the operation of cellular switchgear is ecommended. Added safety measures consist of suitably laced "Danger" and "Caution" notices on live parts of the quipment and controller handles; and using clear and bold esignating labelling on all equipment, particularly on the back s well as the front of all switchgear and control panels.

This "permit-to-work" system is also used for all work on ables except low-voltage cables which are normally jointed alive." In addition to a "permit-to-work" card, the cable in uestion is "spiked" and proved dead by the "authorized erson" in the presence of the "competent person" at the point here the work is to be carried out.

In areas covered by the same operating staff the colours of mps used for switch indication and alarm throughout the whole rea should be standardized, to ensure that each colour has the ame significance in every station.

(3) RECORD SYSTEMS OF PLANT MAINTENANCE

It is important that a concise record system should be kept of he plant installed and the maintenance work carried out, and uch a system should represent the complete record of the work rom the date on which the plant was installed. The basis of he system should be simplicity and ease of reference. All rawings and wiring diagrams should be kept up-to-date. Where manufacturers of plant hold master tracings, they should e informed of modifications so that accurate prints may be ssued.

The system favoured is the record card system in which one ype of printed card is allotted to each type of plant. Such ards are arranged for standard gear, and each unit has its ertinent card allotted to it. Each type is given a distinct colour o facilitate filing.

The cards listed below are used by a bulk supply undertaking nd cover maintenance work carried out on plant on a 66-kV nd 22-kV network employing metal-clad switchgear. The ards are 14 in × 9 in and five different types are used:—

(*a*) General record card (for each station).
(*b*) 66-kV and 22-kV switchgear (Fig. 1).
(*c*) Metering equipments.
(*d*) Switchgear operations card.
(*e*) Transformers.

The second set given below are used by an undertaking covering 11-kV and 6·6-kV area distribution networks feeding transformer chambers stepping down to 400 volts. Each record card covers 10 years' work, and the various overhauls and tests are sub-divided. The size of each card is 11½ in × 11 in, and a complete set is kept at each main area substation in a suitable card-index book. On the front of each card are given the particulars of the equipment and serial numbers, the remaining part being allocated to maintenance records. The cards serve the dual purpose of records of plant as well as of maintenance. Station plant has been divided into six main subjects, a card of different colour being allotted to each subject as follows:—

(*a*) Transformer chambers (Fig. 2).
(*b*) Substation transformers and voltage regulators.
(*c*) Substation high-voltage switchgear.
(*d*) Fire-fighting equipment.
(*e*) D.C. generating or converting plant.
(*f*) Batteries, including switchgear.

This particular record system has been developed in order to co-ordinate the procedure in a number of areas in charge of different engineers so that the maintenance in all areas may follow a fixed routine. Pamphlets giving the details of maintenance required on each section of the plant are issued to each area.

(4) SWITCHGEAR MAINTENANCE

(4.1) Oil Purification

A recent symposium of papers has reviewed in some detail the maintenance of insulating oil and its treatment on site.[1] Regarding switchgear, the most important of the physical properties listed in B.S. 148 is the electric strength of the oil, and apparatus should be available to permit this figure to be readily obtained. Deterioration of the oil and low breakdown value may be produced by (*a*) moisture; (*b*) foreign substances in the oil, including fibrous material, dirt, etc.; (*c*) semi-colloidal carbon produced by arcing; and (*d*) impurities resulting from chemical action between the oil and gaskets, internal painting and some insulating varnishes, etc.[3]

Particular care should be taken during overhaul not to introduce impurities into the oil by the use of cotton waste for tank cleaning, filings or emery powder when facing contacts, and to ensure that all joints and covers are tight. The gaskets should be made of a material which will not be chemically acted upon by the oil. The use of compressed-cork gaskets on cover joints for switch and heavy insulating oils has given excellent results. Indoor switchgear cannot be classed as "watertight", and attention must be paid to the heating and ventilation of the station with a view to preventing condensation in the switchgear and such a humidity as will affect not only the oil but the insulation of switchgear and small wiring circuits generally. In London area distribution stations with metal-clad switchgear, extensive use has been made of tubular heaters with loadings of 60 watts per foot mounted in banks on the switch standards and controlled from suitably placed thermostats operating at a "cut-in" temperature of 50° F.

In voltage transformers careful watch should be kept for signs of acidity and sludging; there is a definite rise in temperature in such units and a certain amount of free breathing takes place, although this is relatively small compared with that in a power transformer.

Regarding flash-point, the determination of which is a laboratory test, representative values should be taken infrequently; they are not necessary for routine testing.

The types of commercial apparatus used for purifying the oil fall into two classes, (*a*) centrifugal and (*b*) filter. The performance of modern types was fully discussed in a recent paper.[3]

In the authors' opinion cold filtration of oil is an advantage,

OIL CIRCUIT-BREAKER EQUIPMENT

RECORD CARD

Station _____ *Date of commissioning* _____

Voltage _____ *Type of oil in O.C.B.* _____ *in isolator chambers* _____

Maker and type _____ *Trip-coil voltage and Ref.* _____

Switch rating _____ *Amp* _____ *kVA* *Closing-coil voltage and Ref.* _____

Oil circuit-breaker				Voltage transformer		Control panel		Isolator chambers: Circuit		Isolator chambers: Busbar			Remarks
Oil purified	Oil sample b.d. value, kV	Oil changed, etc.	Mechanism over-hauled	Oil purified	Renewals, etc., of h.v. fuses	Panel cleaned and overhauled	Mods. to wiring	Oil b.d. value, kV	Oil changed, etc.	Oil b.d. value, kV	Oil changed, etc.		Fault reports Notes on operations on fault

Fig. 1*

TRANSFORMER CHAMBER OVERHAUL RECORD CARD

Transformer chamber: Properties No.: Main substation:

Card No.: Number of cards for above chamber: NAME-PLATE PARTICULARS

H.V. SWITCHGEAR RING-MAIN UNIT	Circuit title: C.T. ratios, O/C. Type of protection: Company's Order No.: Date of commission:	Ammeter: Date: Manufactured by:	Unit No.: B.S.S.: Switchgear class: Oil circuit-breaker type:	Volts: Form:	Amp: Serial Nos.:	C.T. No. R: C.T. No. Y: C.T. No. B: C.T. No. Amm.:
H.V. SWITCHGEAR TRUNK FEEDER UNIT	Circuit title: Company's Order No.: Date of commission:	Date: Manufactured by:	Unit No.: Form: Switchgear class:	Volts: Serial Nos.:	Amp: Oil circuit-breaker type:	B.S.S.:
TRANSFORMER covering all units controlled by one switch	Circuit title: Tapping in use: Gallons of oil: Type of cooling: H.V. cables:	Size (kVA): Primary voltage: Primary amp: Company's Order No.: L.V. connections:	Serial Nos.: Secondary voltage: Secondary amp: Date:		Tapping ranges: Impedance %: Type of breather: Manufactured by: Date of commission:	
L.V. CIRCUIT-BREAKER	Circuit title: Serial No.: Manufactured by:	Size in amp: Type of dashpot:	Class: Over-current setting: Date of commission:	Form:	Amp: Time:	Volts:
L.V. SWITCHBOARD	Type:	No. of ways equipped: No. of ways in use:	Manufactured by: Date of commission:			
FIRE EQUIPMENT	Type: No. of gas cylinders:	Gas capacity, lb wt: Weight of each when full:	Date of commission: No. of thermal fuses:		Manufactured by:	

REMARKS:

			1940	1941
H.V. SWITCHGEAR	Oil circuit-breaker	Oil tests		
		Protective-gear tests		
		General overhaul		
	Busbar chamber and isolators	Oil tests		
		General overhaul		
H.V. SWITCHGEAR	Oil circuit-breaker	Oil tests		
		General overhaul		
	Busbar chamber and isolators	Oil tests		
		General overhaul		

			1940	1941
TRANSFORMER Station No..... Size.....kVA	Oil tests			
	Insulation resistance	H.V.–E. H.V.–L.V. L.V.–E.		
	General inspection			
	Filtration			
	Breather inspection	1st quarter 2nd ,, 3rd ,, 4th ,,		
L.V. CIRCUIT-BREAKER	General overhaul			
	Over-current test			
AUX'S	General overhaul			
FIRE EQUIPT.	General overhaul			

Fig. 2*

* Only essential headings are shown

if oil is heated before purifying some impurities may dissolve he oil and pass through the purifier in the dissolved state.
ienerally the centrifugal type is excellent for removing moisture fibrous material from oil, but it requires a special cleaning ɔess when dealing with carbonized oil, while the filter type, ıough readily dealing with carbonized oil, requires a separate mber for moisture extraction. The centrifugal type requires :e attention on site because the necessary variation in output

use of the replacement method, except in those transformer chambers which contain only small quantities of oil.

(4.2) Maintenance Schedule

Table 1 sets out the essential work to be carried out, and covers all voltages and sizes of switchgear. The periods between work are to be treated as a general guide and are based on experience obtained over a number of years.

Table 1

MAINTENANCE SCHEDULE FOR SWITCHGEAR

Work to be carried out	Interval	Special notes
amine o.c.b.; sample oil for b.d. value; check alignment of contacts; nspect and clean explosion pots, turbulator pots, etc.; inspect insulators; :est interlocks	1 yr	In power stations and key switching stations where switches perform frequent heavy duty, 6-monthly interval recommended. When oil has to be drained for this work it should always be purified before breakers are refilled
rify oil in breaker unit, inspect tank linings, barriers, etc.	2 yr	For breakers frequently charging large transformers and high-capacity feeders on h.v. systems of 33 kV and above, interval may be 1 year or less, depending on carbonization experienced
amine breaker mechanism; lubricate link mechanisms; overhaul closing ɔontactor, auxiliary switches; inspect small wiring, insulation tests of d.c. control circuits	1 yr	For breakers frequently operated and situated in dirty or sulphurous atmosphere, interval to be reduced
amine voltage transformer, test h.v. and l.v. fuses, inspect insulators, etc.; ɜample oil for b.d. value and acidity value if suspected; ɔurify oil in transformer	1 yr 2 yr	Watch for signs of sludging and acidity
ɜan control panel, adjust controller contacts, inspect secondary control fuses, d.c. small wiring, mimic semaphores, etc.	1 yr	—
rcuit and busbar isolator chambers with oil-immersed links: sample switch ɔil or heavy insulating oil (penetrol, etc.) for b.d. value, examine contacts and links	3 yr	On h.v. systems where circuit isolators also used for earthing long feeders of high capacitance current, interval to be reduced, depending on frequency of operation. Oil tests at frequent intervals assist to determine interval
rify switch oil or heavy insulating oil in sealed chambers (i.e. current-transformer chambers, link boxes, busbar interconnecting boxes, etc.)	When necessary	If oil drained for removal of current transformers or disconnection it should be purified before replacement: cleanliness of compartment before refilling essential (see 4.5)
amine busbar oil-immersed selector switches; inspect contacts and mechanisms; sample switch oil or heavy insulating oil for b.d. value	2 yr	Applicable to switchgear with selectors in oil-filled hoods. In circuits where selectors frequently operated, inspect on occasion of annual switch overhaul
ısbar and circuit spouts and plug contacts on metal-clad switchgear with horizontal or vertical isolation: clean and grease switch-plugs; clean busbar contacts and spouts	1 yr 2 yr	Plugs included in annual switch overhaul. Cleaning of busbars depends on atmospheric conditions. Indoor switchgear to be inspected after any building work in vicinity. Interval generally greater with vertical isolation. Spouts to be inspected by authorized persons when isolating
spect and clean insulators, operating links, isolator contacts on cellular-type switchgear	1 yr	Cleaning interval to be reduced or increased depending on atmospheric conditions; inspect contacts annually
amine oil-filled metering tanks, housing c.t.'s and v.t.'s; test h.v. and l.v. fuses; inspect secondary connections, clean and grease main plugs and sockets; sample oil for acidity value, if suspected; purify oil	2 yr	—
outine operation of switchgear	3 mth	Particular application to switches not normally operated on system control

tandards for Electric Strength of Oil.
The figure for recording purposes is the breakdown (b.d.) value after the oil has been sampled and tested in accordance with B.S. 148 by quickly raising the voltage to aximum of 50 kV. Oil must be purified or replaced by new oil if it fails to stand the test for minimum electric strength as given below:

Class of oil	Minimum electric strength	
	Before purifying	After purifying
Grade "A" or "B" .. .. Heavy insulating oil	30 kV for 1 min (B.S. 148) 40 kV for 1 min (recommended)	As new oil (B.S. 148) 50 kV for 1 min (recommended)

pends on the condition of the oil, while the filter type will erate for long periods with little attention.
In the London area 66-kV distributing stations with 66/22-kV nsformers of the order of 30 000 kVA capacity, and switch-ar with breaker oil-content of 400 gallons per unit, the oil is rified by means of a portable filter with an output of 450 llons per hour, in conjunction with permanent oil piping and ainage-tank installations.
On 22-kV switchgear with breaker contents of 70 gallons per it, a portable purifier with an output of 70 gallons per hour is ployed. Generally when dealing with breakers of this and wer capacity, permanent piping is not necessary, the oil being ptied from the tank by the centrifuge or filter into special oil ums and again purified when refilling. In substations, purifi-tion of oil on site should be carried out in preference to the

(4.3) Fault Operation

When the oil circuit-breaker is tripped from a protective relay or by hand, thereby interrupting fault current, it is desirable to examine the breaker before it is returned to service. The oil is generally carbonized, and arcing tips on the main contacts are marked and burnt. The tank should be drained, examined and refilled with clean oil, contacts cleaned up or replaced by new ones if badly burnt, contact alignment checked, and the operation of the breaker thoroughly tested before it is returned to service; but at times of heavy system disturbance, involving the tripping of many breakers, it is often necessary to reclose breakers without examination. In such cases a careful record should be kept of switches involved, and examination carried out at the earliest opportunity. Much valuable evidence has often been destroyed by switchboard operators resetting relay signals before taking

accurate particulars; these should not be reset until a complete record of relays involved has been made.

(4.4) Routine Operation

It is important not to neglect the breaker, which normally is not operated on system control; the mechanism is liable to "settle" and stickiness may develop in the link mechanisms, etc. Routine "closing" and "tripping" tests from controller and protective relays at three-monthly intervals are recommended.

(4.5) Heavy Insulating Oils

The use of heavy insulating oils in modern metal-clad switchgear, in sealed circuit chambers, busbar interconnecting boxes, etc., is now extensive. Unlike compound, however, heavy oils have the property of readily absorbing moisture, which is more liable to be held in suspension and not to separate so readily as from more fluid switch oils. The frequency of sampling depends primarily on whether the design of the particular chamber is such as will resist the ingress of moisture and impurities.

For oil used, however, in selector chambers and circuit and busbar isolator chambers requiring periodic drainage for contact inspection, etc., the maintenance time is greatly increased with heavy oil as compared with a Grade "B" switch oil. Due to its viscosity, drainage is slow and hand pumping is generally used; the oil cannot be purified by a standard purifier at its normal temperature. A method of purifying Penetrol consists of first heating the oil in a special heating tank to 180° F before passing it through a filter with water-jacket heating; successful results have recently been obtained with similar oil having a high moisture content by using a centrifuge with the oil first heated to 140° F.

Although the use of heavy oil tends to minimize oil leaks, the authors consider that, owing to the difficulties of handling this oil on site, there is a tendency to neglect the essential examination of contacts, links, etc., in such compartments.

(4.6) Plug-change and Oil-filled Selector Chambers

The disadvantage of oil-filled selector chambers in switch hoods of duplicate-bar metal-clad switchgear is that connections from both bars are brought into a common chamber. An internal electrical failure in the switch hood, and the subsequent explosion, will probably result in a fault on both busbars. The selector is a quicker method of changing bars than plug change; but this advantage is more than outweighed by the electrical separation afforded by the use of removable plugs. The normal maintenance involved with plug-change breakers is less than with selector gear, as no oil is used in the hood, but particular care should be taken to ensure that a good electrical connection exists between the plug and the switch socket.

(4.7) Tripping Circuits

The tripping circuit of the breaker is probably the most important of the control circuits. Too much importance cannot be attached to the necessity of first-class design of auxiliary switches. Although modern types are more robust the authors consider that there is still room for much improvement—the performance of many a well-designed breaker unit has been jeopardized by an auxiliary switch of poor design and construction.

The authors advocate the "healthy trip lamp" circuit now used by many undertakings. This consists of a lamp, with series resistor, in parallel with the tripping contacts of the controller and protective relays. When the breaker is closed, the lamp circuit is completed by the trip-coil auxiliary switch, and the lamp also serves as a "switch closed" indicator. It also proves the continuity of the complete tripping circuit, including fuses.

Some types of switchgear employ the testing jumper for testing breakers in the isolated position where the d.c. circuits to the breaker are of the plug-and-socket type. Such contacts, especially in tripping circuits, are not a good feature, and during operating tests on an isolated breaker the electrical conditions are not the same as when the breaker is in the service position; the use of permanent connections in flexible tubing is a better arrangement.

Following an overhaul necessitating adjustment of any part of the tripping mechanism, it is recommended that a low-voltage tripping test be carried out. Fig. 3 shows a compact portable

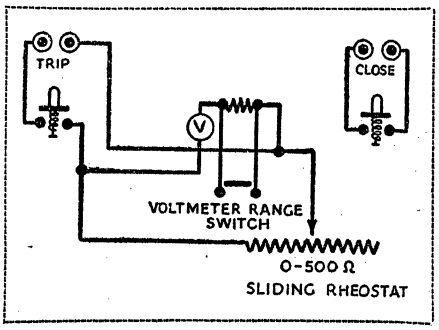


Fig. 3.—Apparatus for d.c. low-voltage tripping tests.

apparatus designed for this purpose. The terminals are connected by flexible leads to the "close" and "trip" terminals of the oil-switch controller, and the breaker is operated from the push-button controls. The resistance is varied until the breaker *just* trips—the voltage across the resistance is given by the voltmeter, and when deducted from the d.c. supply voltage it gives the trip-coil voltage under this condition.

(4.8) Testing of Switchgear Insulation

Although careful visual inspection of insulators, switch-operating rods, inter-phase barriers, etc., should be carried out during breaker overhauls, with particular attention to signs of burning or discoloration and surface cracks on porcelain insulators, the extensive use now made of the fabricated condenser-type bushing calls for special tests to ascertain its electrical reliability. The limitations of high-voltage d.c. testing are appreciated, and modern practice favours the application of power-factor testing as a more definite guide. Information regarding such testing was given in a recent paper[2] in which the whole subject was reviewed in detail.

At a large generating station in London, routine site tests on a number of 66-kV bushings of this type are made periodically.

The desirability of testing facilities embodied in the design in order that tests on individual bushings may be carried out on site is apparent, particularly on multiple arrangements, e.g. on busbars and busbar spouts of metal-clad switchgear. It appears probable that future specifications will call for such facilities.

(5) BATTERIES

Routine attention to batteries used in conjunction with operation of switchgear and plant is essential to ensure that they are kept fully charged and in a healthy condition.

A general overhaul of the charging apparatus should be carried out annually, with particular attention to the testing of reverse-current relays, overload feature of breakers and general examination of all fuses. Automatic change-over switches used for changing d.c. operating supplies from the network to the battery, and in connection with emergency lighting systems, should be tested at least once every 3 months.

Experience has proved that maintenance costs and replacements are considerably reduced on lead-acid batteries if they are given a continual trickle charge instead of a full charge at

iodic intervals. Where station batteries are normally maintained by trickle charge, a capacity discharge test is made once ry 2 years and full details recorded.

Cut-outs situated as near as possible to the battery terminals fitted in order to protect the battery from short-circuit in event of damage to cables between the battery and distribution switchboard. Where d.c. operating supplies are fed from floating battery, earth-fault indication lamps or indicating truments are fitted. Good ventilation of the battery room is ential, this being so arranged that fumes do not come into ntact with any electrical plant. In some installations the ttery room is situated above switchgear and plant, but this has en found to be a bad arrangement, especially under war nditions. Considerable damage has been caused, especially ring air raids, by acid and water dropping on to plant as the ult of this arrangement. Battery rooms should be situated at below plant level, even if this necessitates the use of ventilating ns.

A portable spare battery should be available on a network, of table capacity to provide operating control for switchgear in tributing stations, for use in the event of major battery repair damage. The size of the battery will in general be governed the requirements of solenoid closing; an alkaline battery of)-V 35-Ah capacity has been found suitable for a 22-kV network with switchgear closing currents of the order of 100 A.

The lead-acid type of battery as used in motor-cars has aracteristics suitable for switchgear operation. The cost of battery and of cell replacements is relatively low. Such tteries have recently been installed in two 22-kV stations in London area, but at present there is not sufficient information which to base a recommendation.

(6) TRANSFORMERS

(6.1) General Considerations

1.1) Classification.

The heading "transformers" includes oil-filled reactors, utral-point compensators, voltage regulators, etc., the maintenance of which may be considered similar to that of transformers.

1.2) Acidity and Sludging of Oil.

Although the treatment of oil in transformers as regards rification on site follows very closely that required in switchgear, o factors in addition to the electric strength of the oil require rticular attention, (*a*) formation of sludge, and (*b*) high acidity the oil. Sludge is the result of chemical action, and its rate formation depends largely on the temperature rise within the —it is accelerated by contact with bare metal, particularly pper, and is more prevalent on non-conservator type transmers without breathers. In the early design of transmers the formation of sludge was probably the greatest uble, and much attention was paid to the refinement of oil to nimize it; a highly refined Grade "A" oil was produced which doubt had good non-sludging properties but which had the advantage of releasing its acid content very readily.

As design progressed, far more attention was paid to the iciency of the cooling system and to copper and iron losses and mperature gradients throughout the oil; conservators were ted to remove the free breathing space inside the transformer, d breathers were employed to prevent moisture and impurities om entering the oil. The effect has been to reduce sludging d to enable a more stable oil, Grade "B," less prone to acidity, be used. A great deal has been written on the subject of dging and acidity,[1] but the following summary may be of sistance in a maintenance programme:—

(*a*) High acidity value and excessive sludging in large transformers with forced cooling by means of oil pumps, radiators and forced-draught fans are rare, probably because of the attention given to the cooling and ventilation generally, and also on account of a certain margin of control of the normal oil temperature by temperature instruments, with adjustable "cut-in," for controlling the forced cooling. A top oil temperature of 65° C has been adopted for the "cut-in" point of forced cooling plant on a number of 66-kV transformers of this type with natural cooling up to 60% of full load.

(*b*) Self-cooled indoor transformers are more prone to acidity than outdoor—probably owing to less efficient ventilation.

(*c*) An acidity figure of 0·5 mg KOH per gramme of oil with conservator-type transformers fitted with breathers, particularly if Grade "B" oil is employed, can readily be maintained, and an acidity value not exceeding 1·0 mg KOH per gramme of oil can be accepted in a system using large numbers of non-conservator type transformers employing Grade "A" oil.[3]

(*d*) The rise of acidity as well as its value should be carefully watched.

(*e*) Acidity and sludging can be minimized and checked, before reaching limits which may prove damaging, by:

(i) Regular purification of the oil by centrifuge or filter.
(ii) Attention to the ventilation of the transformers.
(iii) Fitting of conservators and breathers.
(iv) Regular inspection of the unit and taking of oil samples for acidity tests at regular intervals.

In a well-maintained network the probability of excessive acidity occurring only in small units and as isolated cases at present seems to justify the replacement of acid oil by new oil from stock, and the return of the acid oil to refineries where it can be treated at small cost.

(6.2) Maintenance

It is recommended that a tap-change transformer should be treated as two independent units:—

(*a*) The transformer unit, in which the oil is heated by direct contact with the coils; carbonization of the oil is improbable, but regular treatment by centrifuge or filter is necessary to remove sludge and impurities from the oil.

(*b*) The tap-change unit, in which the heating of the oil is indirect through the common partition to the transformer unit. Sludge and high acidity value are less likely to occur, but carbonization of the oil will take place owing to the arcing of contacts or diverter switches. The tap-change unit should therefore be treated as an oil circuit-breaker.

On transformers of 10 000 kVA capacity and upwards, with oil content of over 1 500 gallons, a drainage tank common to a number of units is desirable. This greatly facilitates examination of the main unit and tap-change unit and enables drainage to take place without using excessive numbers of oil drums.

The schedule in Table 2 shows recommended intervals for carrying out maintenance requirements.

(6.2.1) Oil Testing and Purifying.

The frequency with which acidity figures should be taken depends very largely on the design, temperature conditions and loading of the unit. With conservator-type transformers with Grade "B" oil and breathers in main stations where good ventilation is obtained, the period between tests can safely be extended to 2 years. In view, however, of the small extra work involved relative to the importance of the figure, the annual test is desirable.

The circulation method of oil purification on the transformer consists in connecting the centrifuge or filter to the drainage valve at the bottom of the transformer tank and delivering the clean oil to the conservator or top of the tank. When oil pumps with detached radiators are used for forced cooling, the pumps should

Table 2

MAINTENANCE SCHEDULE FOR TRANSFORMERS

	Work to be carried out, and Section Ref. No.	Interval	Special notes
TRANSFORMER UNIT	Sample oil for electric strength (b.d. value),	1 yr	Oil samples taken from bottom of transformer tank and tested in accordance with B.S. 148
	Sample oil for acidity, (6.2.1)	1 yr	If figure exceeds 1·0 mg KOH per g, oil should be treated or replaced
	Purify oil by circulation, (6.2.1)	3 yr (max.)	Circulation to approx. 3 times volume of oil. With transformers operating at high temperatures and load factors, 2-yearly purifications recommended
	Inspect external insulators and oil-filled bushings; sample oil for b.d. value, see Reference (2) on page 18.	1 yr	Cleaning interval depends on atmospheric conditions; further inspections of insulators carried out after cleaning
	Insulation resistance tests of main windings, (6.2.2)	1 yr	Has value as comparative test. Routine tests taken at same temp.
	Inspect connections in transformer, (6.2.2)	3 yr	Particularly applicable to small non-conservator type units
	Inspect explosion diaphragms, replace fractured ones	1 yr	A fractured diaphragm results in free breathing
	Attend to leaks, valves and checking of oil-levels	1 yr	—
	Inspect breathers, (6.2.3)	3 mth	Replacement period depends on atmospheric conditions
	Test temperature alarms, etc.	1 yr	Calibration of temperature indicators to be periodically checked
FORCED COOLING	Examine and overhaul oil pumps, blower motors, blower control panel and operating contactors; insulation tests on control circuits	1 yr	Interval to be reduced where pumps run continually; controls to be tested quarterly; temperature instruments for automatic operation to be periodically checked
TAP-CHANGE UNITS	Sample oil for b.d. value and acidity value, (6.2.1)	1 yr	Sample as for main unit
	Purify oil, examine selector contacts and diverter switches; check oil-levels, etc., (6.2.1)	When necessary	1 year considered to be maximum interval
	Overhaul tap-change control gear, auxiliary switches, operating contactors, remote indication, etc.; insulation tests on control circuits	1 yr	Many designs embody electromagnetic brake for motor control; brake linings to receive special attention
	Inspect breathers, (6.2.3)	3 mth	Replacement period depends on atmospheric conditions

be run during circulation to ensure that all the oil is purified. When using filters, a very good guide to the impurities in the oil is to observe the pressure gauge generally fitted to the input side of the pack. Circulation should continue until the pressure remains steady for several hours.

The risk of fire when purifying oil in transformers is not great, provided reasonable precautions are taken. Oil vapour, however, is prevalent and smoking should be prohibited on site. The use of metallic hosing is recommended, with an earth connection between the purifier and the transformer tank. Blowlamps should not be used for easing inspection covers, and, if chisels are used, care should be taken to avoid sparking. The use of bronze chisels is recommended. "Cracking" of oil, however, is very dangerous and has been the cause of serious accidents. It is due to severe overheating or discharge in the oil, and is more probable after a transformer fault. Oil in this state has a low flash-point and smells of acetylene, and special precautions should be taken if this smell be detected; also the oil must be replaced. Such cases, however, are rare and, provided the oil has a normal smell, flash-point figures need be checked only occasionally.

The period of purification of oil in the tap-change unit varies considerably between different makes and designs, and it is not possible to give any fixed time for this work. Carbonization of oil in some types is relatively heavy. The method of determining this figure is to keep an accurate record of all on-load tap-change operations after installation and to make frequent examinations until a suitable period based on the number of operations is arrived at—cyclometer dials on tap-change mechanisms are very useful in this respect.

(6.2.2) **Insulation-Resistance Tests and General Inspection.**

Insulation-resistance tests carried out on high- and low-voltage windings of transformers in service have a value based on comparative records taken over a number of years. Generally the reading includes the insulation resistance of cables, cable boxes and circuit spouts of switchgear permanently connected to the transformer, while the greatest influence is the temperature of the transformer when the insulation-resistance reading is taken, particularly on large units. For the reading to give a reliable indication, routine tests should be taken under similar conditions as far as possible. The tests may be treated as an extra routine precaution in maintenance, but for the detection of moisture reliance should be placed on measurements of the electric strength of the oil.

The inspection of the tank and windings on large conservator-type transformers is a major operation, which is generally outside the scope of site facilities. Inspection covers are fitted which permit of a certain amount of examination of the general condition of the top of the tank, cores and windings, particularly primary connections to bushings. Such an examination is limited in scope. During routine purification of the oil in conservator types, an inspection of the internal condition of the conservator tank for signs of scaling or corrosion provides a check on the efficiency of the breathing system.

In small transformers of the non-conservator type the removal of the top cover is a relatively easy matter, and advantage should be taken of this to inspect the main copper connections and to clean insulators above oil level while carrying out routine purification of oil. The tank and cover should be carefully inspected for signs of corrosion, and the cores and windings for sludging and acidity.

Tanks, radiators, fins and tubes, etc., should be inspected for signs of external corrosion. Periodic painting is recommended and the use of high-pressure spraying has been found the most effective method.

(6.2.3) **Breathers.**

The importance of efficient breathers cannot be too greatly stressed, and their inspection and re-charging must be given

ticular attention. Silica-gel breathers offer advantages in intenance because they are partly regenerative, easy to fit, l less messy than calcium chloride; the moisture absorbed may driven off by heating the contents, and replacements can be ried round during inspection and quickly changed where essary. During inspection it is equally important, whatever e is employed, to ensure that there is no clogging of the air ake pipe or gauze between the breather and the outside atmo- ere, or between breather and conservator.

(7) TRANSFORMER CHAMBERS

Jnder this heading are included substations on consumers' mises and transformers in street pits, with a supply voltage 11 kV or less, the whole equipment being regarded as a "unit." ile the maintenance of switchgear and transformers in these sitions will generally follow the lines laid down in Table 1 l Table 2 respectively, the "time factor" is likely to be varied ing to widely differing local conditions.

Adequate records of the plant are essential, as shown in . 2. In view of the large number of transformer chambers is useful to have a "general information" card index record l a similar record of earth-plate details. Sufficient attention ot always given to bold and conspicuous labelling of switch- ar in transformer chambers. This should be carried out on '. and l.v. switchgear, unit boards, etc.

The maintenance of plant in these situations is governed by selection of the most suitable plant in the first instance and acquiring sufficient information in regard to loadings to able reinforcements to be carried out at the correct time.

Usually the distribution engineer has anything but a free oice in the siting of these transformer chambers. Space is ually restricted, ventilation bad and access often difficult. part from the financial aspect, there is seldom room for spares, d it is desirable to lay-out the plant so that any one item n be removed and replaced without disturbance of any other ant installed. Standardization of switchgear and transformers ould be aimed at, and confined to as few sizes as possible; r example, 150 kVA, 300 kVA and 1 000 kVA for transformer pacity is a reasonable range, for either single or multiple units. To facilitate replacement of transformers, a design of cable ox is used which can be moved sufficiently for a change of ansformer to be made without breaking down the cable rmination.

Routine maintenance of transformer chambers in factories is rmally confined to external cleaning of plant, but arrange- ents can usually be made, at least in time of peace, for a com- ete shutdown at week-ends. This should be approximately on annual basis, and the whole of the plant should be examined. ansformers should have oil samples taken for electric-strength id acidity tests; all main connections should be examined, oil- vels checked, and a general visual inspection made of the trans- rmer and tank.

The maintenance work carried out on switchgear, as regards l samples and general examination, should be planned on the es laid down in Table 1. The actual time-interval between spections will largely depend on local conditions; plant exposed heat and dirt should be inspected more frequently than is ggested in the Table.

Practical experience indicates that heat is a factor which makes r acidity. This is confirmed by A. A. Pollitt,[4] who states at the rate of chemical reaction is doubled by each 10 deg C se in temperature. In transformer chambers with bad venti- tion, and in street pits with little or no ventilation, maintenance likely to be excessive unless steps are taken to reduce the eat to be dissipated. Considerable success has been obtained y a transformer design which reduces the iron and copper losses by as much as 40% for an expenditure of not more than 20% in excess of the normal transformer cost. The additional capital expenditure is fully justified by the reduced maintenance costs, particularly where high load factors are obtained.

The entry of moisture, and therefore of oxygen, can be prevented by the use of a hermetically sealed transformer fitted with an expansion chamber. Pollitt's statement[5] that no attempt has been made to produce such a transformer in this country is not borne out by the facts, for transformers so designed have been in use by several British undertakings for the last 10 years and have proved very successful. The combination of hermetically sealed tanks with the low-loss transformer design mentioned above has reduced maintenance of transformers, particularly in street pits, almost to vanishing point.

The frequency of inspection is also affected by the loading of transformers in these positions, and therefore accurate load records are necessary. With many transformer chambers and street pits it is impossible to obtain satisfactory records by means of visiting attendants; the only reliable method is to install thermometers of the maximum recording type in each transformer and in the surrounding air, and a maximum-demand ammeter in each phase of the l.v. output.

The information obtained from these instruments gives a positive record, and, coupled with an integrating meter, allows the load factor to be computed. This gives the distribution engineer considerable guidance in fixing the frequency of inspections, and the necessity for reinforcement, and enables him to use transformers to the reasonable limit of their capacity without going beyond the point where excessive maintenance, or possibly breakdown, would result.

Where large numbers of this type of transformer chamber are employed on a distribution network it is desirable to standardize plant and to simplify switchgear as much as possible. For voltages below 11 kV consideration should be given to the question whether in transformer chambers it is better to employ a simple form of non-automatic ring-main unit operating in oil, rather than switchgear with automatic operation, or ring-main units with fuse control. Maintenance of switchgear would then almost disappear and yet the measure of isolation required for normal working would be obtained. This suggestion is based on the authors' experience that transformer faults are rare provided that the original design is good and efficient maintenance is carried out. They have found that the majority of faults on cables of 11 kV and less are caused by mechanical damage.

If some local protection is considered essential, it is desirable to dispense with automatic switchgear in transformer chambers and street pits and substitute fuse control of the h.r.c. type on both sides of the transformer, as with this arrangement there is less maintenance work to carry out. A further reason for the use of h.r.c. fuses, or of no fuses at all, is that where individual consumers or networks are being supplied service to the consumer is paramount, and it is not generally desired that transformers shall be switched out because of overloads. Switchgear should not operate except on a fault amounting to a short-circuit.

The methods of obtaining records suggested earlier in this Section should ensure that overloads are well catered for. The views which have been expressed with reference to maintenance of transformer chambers apply also to transformers installed in pits in the street, where the question of temperature is of even greater importance.

All distribution engineers are well acquainted with the lack of interest and consideration given to their needs by architects when planning new buildings, and it is hoped that some improvement

may be looked for in post-war reconstruction, not only as to space and ventilation but also regarding access for transporting plant from the public highway.

(8) FIRE-FIGHTING INSTALLATIONS

(8.1) General

The problem of the fire protection of plant, which has been fully discussed elsewhere,[6, 7, 8] can be divided into two parts: (*a*) Extinguishing the fire by limiting the flow of burning oil into a confined space, where it may be effectively extinguished by fire-fighting appliances. (*b*) Limiting the size of that space by dividing sections of plant into a number of fireproof compartments.

In planning new stations, particular attention has been given to the layout of plant and buildings in accordance with the recommendations referred to, but in older stations the problem is not so straightforward. In these cases considerable use has been made of fireproof screening of a type using heat-resisting material compressed between two perforated steel sheets. This possesses good mechanical rigidity and is used for partitions and canopies for plant, and as a means of enclosing cable and multi-core runs in vulnerable positions. Further precautions consist of fireproof taping around cables, particularly between cable boxes and floor level; the use of sand or pebbles in open cable trenching; catchments under the switchgear and retaining walls round transformers, with adequate drainage pipes where necessary; the sealing of all holes between switchgear floors and cable basements; and the use of automatic fire-fighting installations.

It is important to use different routes for d.c. supply cables for each section of the switchgear. Circuits common to a number of units should be interconnected either at the control panel or, if at the switchgear, in tubing preferably below floor level; so that the failure of a switch unit, causing explosion or fire, will not affect the operating circuits of adjacent equipments.

(8.2) Maintenance Schedule

Table 3 gives a maintenance programme for automatic installations and portable extinguishers.

(8.3) Automatic Installations

Indoor switchgear is far from watertight, and much care is taken on site to avoid excessive humidity or condensation. The use of water for extinguishing fires on such plant is undesirable since if water comes in contact with the healthy units of the section there will be considerable delay in re-commissioning, and possibly serious trouble. The use of gas under such conditions has considerable advantages.

Station batteries are generally used for supplying booster pumps for water installations. A certain minimum pressure is required for foam systems using water supplies; this is obtained by a booster pump or from the pressure head of a water storage

Table 3

MAINTENANCE SCHEDULE FOR FIRE-FIGHTING INSTALLATIONS

	Type	Work to be carried out	Interval	Special notes
AUTOMATIC INSTALLATIONS	Water	Log water pressure Log air-detector line pressures	Weekly Weekly	Air lines liable to condensation to be drained quarterly; lines to be recharged with air as required
		Routine-test motor and control gear	1 mth	On some systems motors operate if water pressure drops below a certain mark owing to valve leakage. This test is inclusive of such operations
		Check indication and alarm systems	3 mth	Test by operation of drainage valves in each section in turn
		Examine and overhaul motor and motor control gear	1 yr	Liquid starters to be topped up as required. If storage tanks have automatic filling, examination to be made of ball valves, etc.
		Examine detectors, nozzles, etc.	1 yr	Where possible make test by discharging installation for short period on outdoor switchgear and transformers; main filters to be cleaned
	Gas, CO_2 or methyl bromide	Weigh cylinders	1 yr	Cylinders of more than 10 % drop in weight to be recharged. First check 6 months after installation
		Check automatic and manual valves. Operate gas-release mechanism, inspect nozzles, etc.	1 yr	Where portable nozzles with reeled tubing are embodied in installation, tubing to be carefully inspected for deterioration
		Check indication and alarm systems	3 mth	—
	Foam	Test opened drums of foam powder or liquid; overhaul booster pump and control gear; routine-test motor and control gear	1 yr 1 mth	Take samples and mix with water to check adequacy of foam; powder types—inspect for "caking" or signs of moisture; dry all mixing chambers after test
		Test contents in 2-liquid type	1 yr	Test for reaction by samples of each liquid
		Check automatic and manual valves	1 yr	—
		Examine sprays, etc.	1 yr	Pipes checked by compressed air
		Check indicating and alarm systems	3 mth	—
PORTABLE EXTINGUISHERS	Foam portables and engines	Inspect all valves and nozzles, test contents	1 yr	Test for reaction by samples from inner and outer containers, according to particular make
	Gas cylinder equipments, CO_2 and methyl bromide	Weigh cylinders	1 yr	Particular attention to condition of hoses
	Soda-acid	Inspect valves and nozzles, test contents	1 yr	Test for reaction by samples. Alkaline solutions need changing every 2 years in most types
	Carbon tetrachloride	Check that containers are full	1 yr	CCl_4 volatile, does not deteriorate
Water and foam hydrants		Inspect valves and hoses	1 yr	"Wet" test canvas hoses for water or foam; inspect for deterioration
Breathing masks		Inspect condition, test pressure in cylinders	1 yr	Keep apparatus in box, in cool dry position

tank. Where standby petrol-driven pumps are used on water and foam installations, they should be tested once every month. Water storage tanks are desirable, especially under war conditions, both on water and on foam installations.

Hand-controlled isolating valves should be fitted to all main sections, so that any section can be isolated after operation and the installation quickly made ready for further service.

Air-detector lines for outdoor plant should be carefully installed so that drainage, necessitated by condensation, can be carried out in every section. Careful assembly of all pipe joints and valves is imperative so as to avoid small air leaks, which are often difficult to locate and may lead to inadvertent operation.

On water installations the systems should be drained annually, and filters on the main bus piping should be thoroughly cleaned. Spare valve seatings for automatic water valves, together with spare detectors, should be readily available.

Gas fire-fighting installations possess the advantage that no external supplies are needed for operating them, except where electrical detectors are used. Where the same battery of gas cylinders is used to cover sectionalized compartments of the plant a reserve battery is necessary to take care of a further fire in any section, and to cover the period when cylinders are being replaced and recharged. In a number of substations, the arrangement adopted is a battery of cylinders operating from automatic control with a similar battery in reserve, controlled from a centrally situated manual control panel. Special anti-vibration trip toggle releases are fitted to all installations. To provide adequate ventilation for indoor transformers screened for gas protection, use has been made of ventilating partitions at the lower parts of the enclosure, which drop under gravity when released by pressure switches operated by the gas on discharging.

Gas can be applied either by flooding a completely enclosed section or, as has been adopted in some large 22-kV indoor substations, by releasing it in a partially enclosed space formed by partitioning at the back and two sides of sections of switchgear, leaving the front open. This arrangement has been found effective and is economical in gas where the cubic capacity of the switch-house is considerable. The ideal application, however, is the ability to flood an enclosed section with the necessary concentration.

The independence of the gas installation, together with the small space required for cylinders and low maintenance costs, makes it an admirable medium for flooding transformer chambers in vulnerable positions.

(8.4) Safety Precautions

Provision should be made for suitable emergency exits from all fireproof compartments. Manual control of automatic fire-fighting installations is adopted in sections where maintenance work is proceeding. This is not because of the danger arising from the fire-fighting medium but because of the risk of inadvertent operation of the installation by possible damage to detectors while personnel are working on the top of high switchgear and transformers, with the possibility of their meeting with serious accident should the installation discharge. Breathing masks fitted with air-storage cylinders are of great assistance in dealing with smoke and fumes, and should be available in every station.

(9) PROTECTIVE GEAR

(9.1) General Considerations

The basis of sound protective gear is simplicity, and a careful consideration of system layout relative to the protective gear necessary may avoid the use of highly complicated arrangements with their attendant excessive maintenance demands. The necessity of quick-acting discriminating protection on main trans-

Table 4

MAINTENANCE SCHEDULE FOR PROTECTIVE GEAR

Standard Tests on Every Equipment.
(1) Insulation tests on small wiring of protective current transformers, inspection of connections at termination blocks, multi-core cables and control panels.
(2) Testing of breakers connected with unit, including tests on tripping and intertripping, alarm and indicating circuits and relay signals.
(3) Inspection of relays, with particular attention to plug bridges, d.c. contacts and air-gaps of induction-type relays.

Type of protection and Section Ref. No.	Type of relay	Additional maintenance tests
Discriminating pilot-wire protection on feeders using circulating-current or balanced-voltage principles, (9.3.4)	Instantaneous	(1) Insulation and loop-resistance tests on pilot (2) Operation by secondary injection from c.t.'s at each end (3) Stability check on load
Restricted earth-leakage protection on transformers; balanced earth-leakage protection on reactors, etc., (9.3.5)	Single-pole i.t. induction	*Core-balance types.* (1) Stability tests by primary ampere-turns injection: applied to transformers with separate neutral c.t. and to balanced earth-leakage on reactors (2) Operation tests by primary ampere-turns injection from each c.t. (3) Stability check on load *Electrical-balance types.* (1) Operation tests by secondary injection from each set of c.t.'s (2) Stability check on load For a star-connected transformer with neutral c.t., check stability by circulating primary current between each line and neutral from a generator or testing transformer
Overall circulating-current protection on transformers	3-pole i.t. induction or 3-pole instantaneous with "kick" fuses	(1) Insulation tests on pilots (2) Operation tests by secondary injection from each c.t. (3) Check relay current with transformer charged from one side (4) Stability check on load
Busbar-zone protection (balanced earth-leakage), (9.3.7)	Master a.c. relays of single-pole i.t. induction type	(1) Balance tests by primary ampere-turns injection (2) Test operation of d.c. contactor: check balance tests with contactor closed (3) Operation tests of each master relay by primary ampere-turns injection (4) Check timing relays (5) Test operation of tripping relays from each master relay (6) Individual tripping tests on each circuit (7) Test alarm circuits
Over-current protection on all equipments. Unrestricted earth-leakage protection for: Busbar-zone protection Sectionalizing points, etc. (9.3.3)	Inverse-time nduction Instantaneous Inverse-time induction	(1) Operation tests by secondary injection from c.t. terminals; timing tests, using electric timing clock, to be carried out periodically on induction types (2) Check current in earth-leakage relays on load
Buchholz protection on transformers		Test tripping and alarm by introducing air under pressure between transformer and float chamber

mission systems is evident, but on distribution networks of suitable layout much simplicity can be obtained by the application of over-current and earth-leakage protection. The bulk-supply system of one London undertaking consists of a number of generating stations interconnected by a network of 66-kV and 22-kV feeders, which, in turn, supply a number of distributing stations throughout the area. The two networks are earthed through earthing resistors at generating stations and distributing stations. The commissioning and maintenance of all protective gear is carried out by a protective-gear engineer and assistants, centrally located; at the points of supply to other undertakings testing is carried out in co-operation with the engineers of these undertakings.

Current transformers for balanced protective schemes are installed for that purpose only, and 3-pole inverse-time over-current relays, operating from instrument current-transformers, are installed as standard equipment on all units. In balanced protection the minimum ratio of relay operating current to current available is 1 : 3.

(9.2) Commissioning

Careful installation and initial testing of protective gear are important,[9] for incorrect commissioning leads to faulty performance with far-reaching effects which may necessitate considerable maintenance and jeopardize the continuity of supply.

Short-circuit tests from an isolated generator, preceded by careful checking, are carried out where possible as a final check on stability of balanced systems under through short-circuit and earth-fault conditions, and for operating tests with internal faults; new plant is brought slowly up to normal voltage before being connected to the system.

(9.3) Maintenance

(9.3.1) **Schedule.**

Table 4 is a schedule of protective gear installed on various units of the network under consideration. Col. 3 gives details of special maintenance, additional to that carried out as standard routine on every equipment. Routine tests are carried out annually.

Thermal milliammeters are used for measuring spill currents in relays on balanced schemes.

(9.3.2) **Secondary Injection Testing.**

Routine testing of all equipment except main station generators is carried out entirely by injection. In injection testing, small single-phase portable transformers are used, the connections of a typical unit being shown in Fig. 4. An advantage of this method is the large measure of control for calibrating and also the low power input of the supply. Test windings are not embodied in current transformers except in isolated cases of the bar-primary type, where testing is facilitated by embodying a copper testing primary brought out to a suitable testing block. Multi-point test switches are not used; the authors prefer the use of bolted connections where possible, with studding of a minimum size of No. 0 B.A.

(9.3.3) **Relays.**

Relays should be well protected by means of closely fitting dustproof covers and the use of dustproof lead-in bushes for the terminals. Much ingenuity has been displayed by manufacturers in designing relay signals of different size, colour and shape, and standardization here is long overdue.

The d.c. contacts of the relay should receive careful attention; the authors prefer the type embodying a definite wiping action, as compared with that which relies solely on contact pressure. Contacts should be kept clean, and if abrasive paper is employed for this purpose it should be of the finest grade, as used by instrument makers. Silver contacts often become oxidized, but this does not appear to affect tripping.

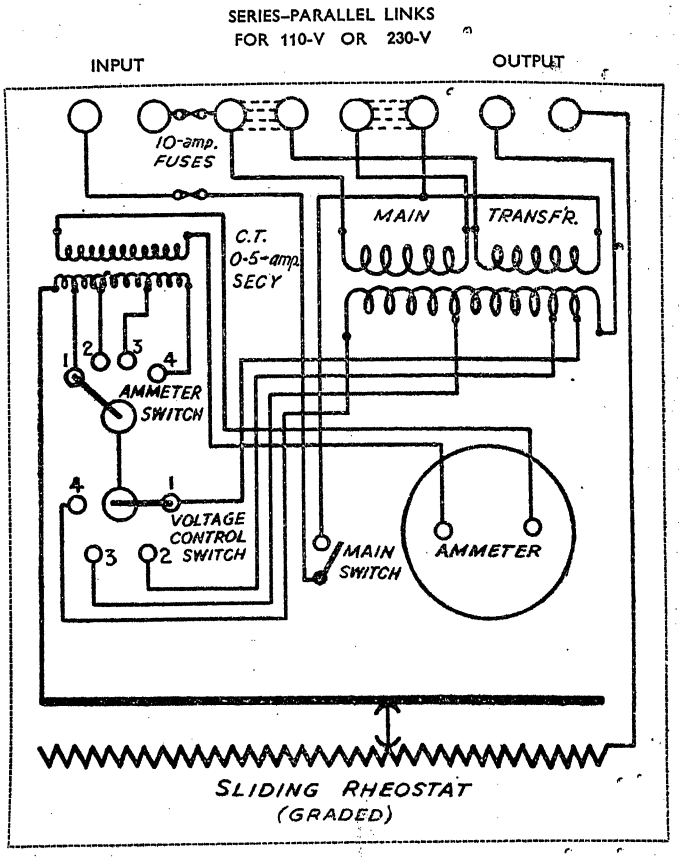


Fig. 4.—Secondary injection transformer.

Ammeter switch		Voltage control switch	
Stop	Range (amp)	Stop	Output (volts)
1	0–30	1	5
2	0–10	2	10
3	0–5	3	20
4	0–1	4	50

Short-time rating on all windings approx. 250 VA. Outside dimensions 8½ in × 8½ in. × 7 in. Weight 18 lb.

Contact resistance is especially liable to give trouble on circuits operating with a tripping supply of less than 100 volts, and particular attention to contacts is required on systems operating below this figure.

Some relays are provided with an external tripping device, but in general this feature is being abandoned. Unless such a device is carefully designed and has a positive lock to give protection against direct pushing, inadvertent tripping by cleaners will probably result.

During tests on induction-type relays with inverse-time characteristics, it is important to check the minimum operating current. This test may also reveal faulty jewels or pivots, which generally result in jerky movements of the disc or drum. Variations in timing sometimes occur through ageing of the brake magnets. The gaps between brake-magnet poles and pole faces of operating coils should be carefully inspected and cleared where necessary. Steps should be taken to ensure that the zero setting on the time scale coincides with the closing of the trip contacts.

Where induction-type over-current and earth-leakage relays form the sole protection, and where they are used for important system-sectionalizing points, their timing should be tested annually. When such relays are used for back-up protection this period can be extended according to experience of the

particular design. Induction-type relays hold their calibration well, and the careful checking of the minimum operating current will often disclose mechanical and electrical faults; the calibration is sensitive to wave form, and when injection transformers are used for timing tests on site their output characteristics should be checked; resistance control from a low-voltage mains supply is preferable.

Multi-point tripping relays should be tested for minimum operating voltage, i.e. at 50% normal voltage, and latch mechanisms checked for stability on vibration.

Where relays are mounted on swing frames under switchgear, contacts and movements should be carefully tested to make sure they are vibration-proof. They are liable to damage, especially when switch trucks are used, unless particular care is taken.

Mechanically operated relay signals offer advantages over electrically operated types; a series coil appears to constitute a weak link in the tripping circuit, as it is not possible to cover it by a "healthy trip" lamp unless the coil connection is brought out to a relay stud. Much elaboration can be avoided by the use of a "free handle" alarm system. This system has the dual advantage of giving audible alarm should the breaker trip from vibration or from "slipping" of the mechanism, and also in being distinct from the tripping circuit.

(9.3.4) **Feeder Protection.**

At times when balance tests of pilot-wire protective gear on load are being carried out, the back-up over-current relays should be set so as to afford complete protection.

Before the war, pilot-cable testing was carried out annually and the experience of many years justified this practice. In war time there is the possibility of pilots being pulled or strained as the result of bombing, and so pilot-cable tests are carried out in the areas affected after each air raid. Apart from insulation tests by means of a 500-V insulation tester, loop-resistance tests are necessary in schemes depending on the resistance of the pilot circuit. On screened pilots used in a type of balanced-voltage protection with screens cut approximately half-way, capacitance tests on the screens are also carried out by applying 110-V a.c. earthed supply to each core and measuring the induced voltage to earth on each half of the respective screens. The provision of pilot termination blocks with removable pilot links greatly assists such work, but they should be of robust design with bolted connections and well-fitting covers capable of being locked.

(9.3.5) **Transformer Protection.**

Although electrical balance has been used in some cases, restricted earth-leakage protection has most generally been applied by a core-balance current transformer covering the delta windings and main cables, and on the star side either by one transformer embracing the line cables and neutral or by an additional transformer round the neutral cable. Current transformers are mounted as near to the switchgear as possible. The method of testing for balance in the latter case is by passing a number of turns round each transformer, circulating current supplied from an injection transformer, and measuring the spill current in the earth-leakage relay. By this test, stability at a high value of primary ampere-turns can be obtained with a low power input.

Intertripping between the h.v. and l.v. breakers is carried out by: (1) 3-point earth-leakage relays where the same d.c. supply is used; (2) two separate tripping circuits on each relay with breakers using different d.c. supplies. Three-pole over-current relays on each side provide phase-fault protection; in the case of transformers feeding a distribution network, 3-pole over-current relays on the l.v. side only are used in some cases, with intertripping to the l.v. breaker. An advantage of having over-current relays on each side is that in the event of damage or bad connection on the pilots used for intertripping, the back-up value of over-current relays will trip each breaker independently. The advantage of an unearthed d.c. battery in these cases is plain, for it enables normal intertripping to take place should an earth fault develop on the interconnecting pilots.

(9.3.6) **Feeder Transformer Protection.**

This is a combination of feeder and transformer protection. Routine testing is carried out as for each section. Intertripping between the transformer protection and the remote end of the feeder is effected either by (*a*) operating a d.c. polarized relay at the remote end, energized by the operation of transformer protective relays; or (*b*) d.c. injection, applied to feeders protected by a form of balanced-voltage protection by interrupting one phase of the balanced system and injecting direct current across the break.

(9.3.7) **Busbar-Zone Protection.**

With the object of covering earth faults, this has been installed in all 22-kV and 66-kV distributing stations and has been applied to metal-clad switchgear in two forms: (1) single-busbar scheme (applied to small stations); (2) double-busbar scheme (applied to stations taking a supply on each busbar from different sections of the network). A schematic diagram of the double-busbar scheme is shown in Fig. 5. Busbar-section switches are not tripped, and discrimination between two busbars only is attempted.

Step-down transformers with delta h.v. windings fed from the 22-kV network are not tripped by the 22-kV protection. In the 66-kV scheme having 66/22-kV transformers with delta/star windings, the delta side is tripped by the operation of the timing relay and any one of the feeder earth-leakage relays, which embody a separate pair of contacts for this purpose. The 22-kV star side is treated as a feeder and is tripped by the 22-kV protection. Cabled reactors are treated as feeders.

Core-balance types of transformers are used exclusively and testing is carried out by a 4-kVA single-phase heavy-current testing transformer with output at 4 or 8 volts. Flexible cables are used for threading through the transformers or connecting to test-bar primaries.

In the single-busbar scheme no segregation of the bars is attempted. One a.c. master relay is employed, connected across the bars of the mid-point box, to which cables leading to each current transformer are taken direct. The master relay operates a multi-point tripping relay, which gives a tripping supply to the contacts of each earth-leakage relay.

The protection covers faults in cable boxes, but the time-lag of the master relay enables such faults to be cleared either by discriminating or by over-current relays. No intertripping is carried out at the remote end, and, in the event of a fault occurring on the circuit side of a breaker, back-up over-current at the remote end is relied upon.

(9.3.8) **Transformer Chambers.**

When ring-main and transformer units are protected by direct-acting trips shunted by time-limit fuses, an annual test should be carried out by removing the fuses and checking the value of tripping by secondary injection, while intertripping tests should be made between h.v. and l.v. breakers; small wiring should have insulation tests. Particular attention should be paid to ensuring a good contact between fuses and clips, and if the time-limit fuse shows signs of overheating or is known to have passed a heavy current, it should be replaced even if it is not fractured. The d.c. resistance of the coil should be as high as possible compared with that of the fuse, in order that the d.c. component of transients may be by-passed by the fuses; this is also applicable to relay coils shunted by time-limit fuses.

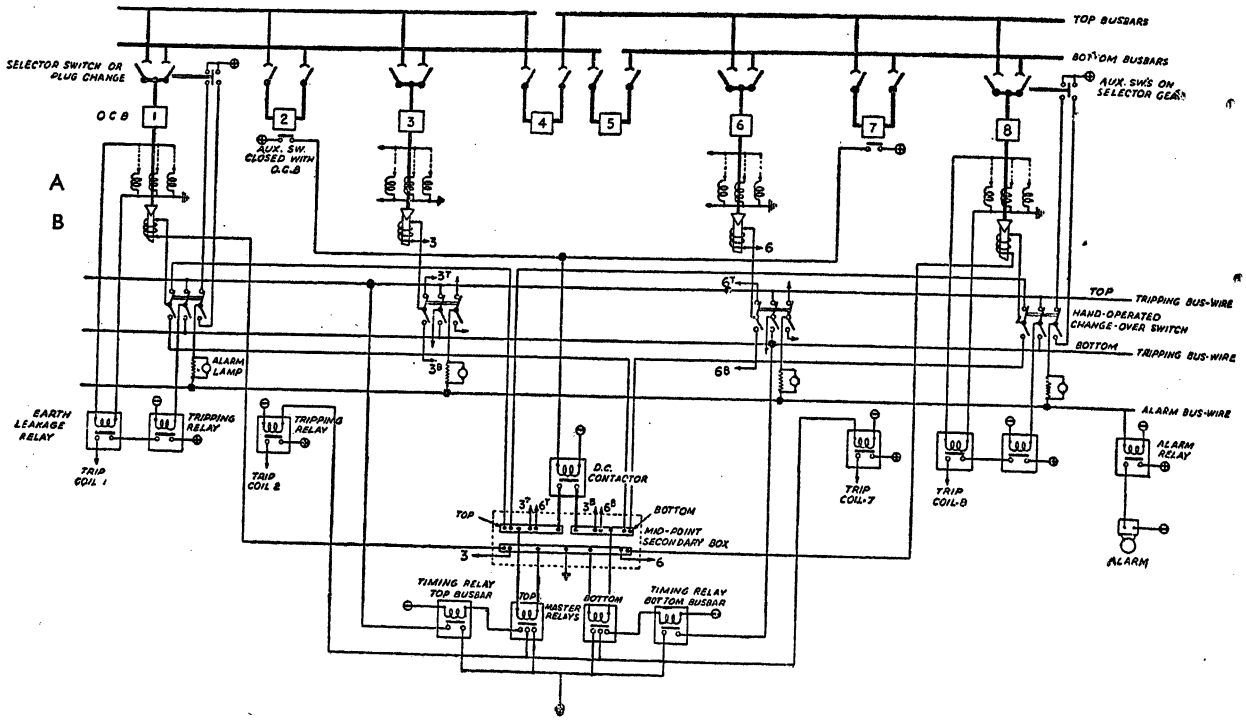


Fig. 5.—Schematic diagram of "double bar" busbar-zone protection.

A. Over-current relay and instrument current transformers. B. Core-balance current transformers.

(9.3.9) **Records.**

Records are kept of all commissioning tests and routine testing, together with full details of any special tests carried out. A relay record card is allocated to each equipment, recording on one side the types of all protective relays, serial numbers, range of relays, current-transformer ratios, etc., while the reverse side is utilized for the settings of such relays with equivalent fault current to operate, and for details of routine testing; each protective-gear pilot cable has an individual record card.

(10) MAINS

(10.1) Records

It is probable that all undertakings base their mains records on ordnance survey maps, the scale of which will vary according to the district, i.e. congested town areas, suburban or rural; and the form of these records will be determined by the actual density of cables in the area. When a new area is being developed, the procedure is straightforward; but when a record is being set up of an area whose development has extended over 40 to 50 years a considerable amount of surveying is involved. Such an area is to be found within the boundaries of a London undertaking. Here the system is composed almost entirely of duct routes, installed over a long period; it has been dealt with by compiling four separate records. The first (Fig. 6) consists of an ordnance sheet, scale 44 ft to 1 in; a dotted line in the Figure shows the existence of a duct route with sections in full detail,

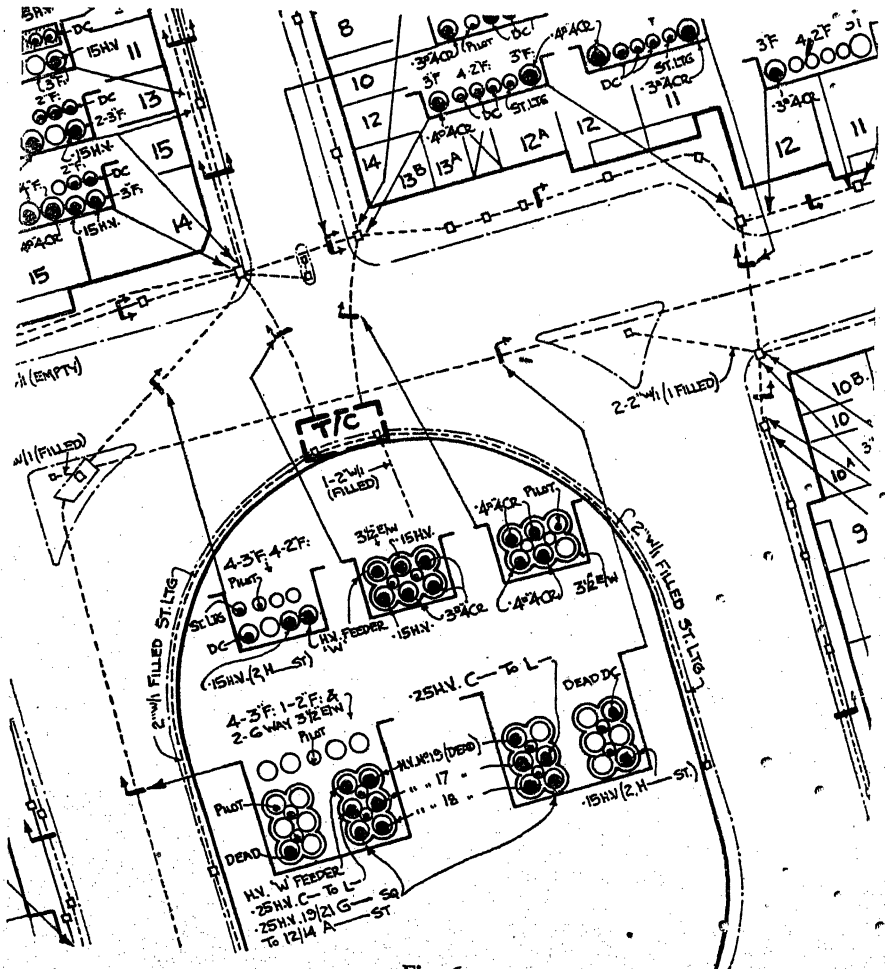


Fig. 6

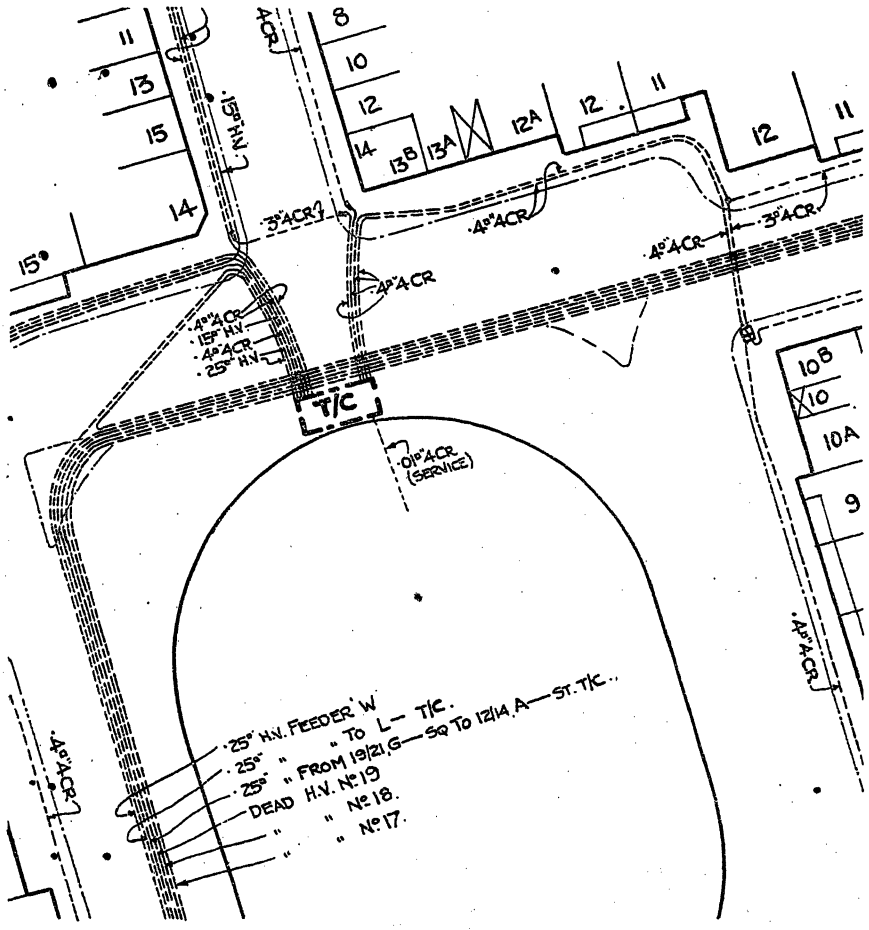


Fig. 7

and also gives an indication as to the cables contained therein. In order that the route of each cable may be traced a second map, of the same scale, is prepared showing the cable routes, together with indications of their nomenclature (Fig. 7). These two maps form the physical record of the existence and position of cables.

For the purpose of operation two further records are constructed, the first being a high-voltage key plan on a diagrammatic basis and the second a low-voltage key map on a geographical basis (Fig. 8).

For an undertaking operating largely in less congested districts and with a mixed system of duct routes and direct-laid cables, ordnance maps (scale, 88 ft to 1 in) have been constructed which show all existing cables by means of various coloured lines, the colouring indicating their type and voltage. These maps are amplified in loose-leaf strip form at a scale of 16 ft to 1 in, and all possible relevant details as to size, type, position, etc., are recorded; house services are embodied, together with an indication of their appropriate phase colour.

In addition, key maps are provided for operational purposes on similar lines to those outlined above. When new construction of a major character, from 11 kV to 66 kV, is taking place, detailed records are compiled daily. A method which has been adopted for this is to bind the completed record of each run as a set of loose-leaf books. This method has the advantage of being suitable for use on site at a later period.

The salient points of this record are shown in Figs. 9 to 13, Fig. 9 showing a page of the index which gives the cable details. Fig. 10 shows a standard "joint hole" on a cable run (11 kV); it will be seen that by arranging the relative positions of each joint so as to be the same at each "hole" very easy identification is obtained. Figs. 11 and 12 show the plan and cross-section of the route, while the final record is shown in Fig. 13, which records the information necessary to assist quick and accurate calculation when locating faults on mains made up of cables of varying cross-sectional area.

These records will require to be amplified when dealing with 33-kV and 66-kV oil-filled cables. Additional information must be recorded during the course of installation, including details of impregnation and flow test of each completed oil section, together with pressure/volume curves of all feed tanks. A final profile of the route (Fig. 14) is prepared in graphical form and drawn to a scale such that the rise and fall of the route is greatly exaggerated in respect of the longitudinal measurement, and the pressure values are therefore more readily measured. Joint positions are marked and numbered, and the feeding points indicated. Superimposed on the profile are the calculated oil pressures at which each section is designed to operate.

Records of the operating values of low-oil-pressure indicating switches are tabulated.

Detailed service records are probably best arranged as a card index system. A card should be allotted to each service and filed numerically in street order. The card should record length, type and size of cable, type and size of cut-out, phase connected on main distributor, and geographical position of joint in the path.

It is essential that maps of existing cables be kept up to date and any alterations recorded daily. The system adopted for ensuring this will depend on the size of the undertaking, but it is essential that the operation key maps should show "breaking points" in both h.v. and l.v. networks and details of links in disconnecting boxes on a daily basis.

A useful record is a card index for each disconnecting box, the full details being entered on a separate card which should show location, type, capacity, date installed, and a small sketch of the layout of the cables connected. These cards should be filed in street order and the reverse side utilized for recording reports of inspections. A similar card-index record for drawing-in boxes where duct routes exist is desirable; each card would record location, size, type of construction, and details of contents. Duplication of all records is essential.

(10.2) General

Where multiple duct routes are laid, maintenance work, whether routine or breakdown, is considerably assisted by clear and accurate labelling of every cable in every drawing-in box, in addition to the keeping of accurate records. A good method is to use a stamped lead label "plumbed" longitudinally on the cable sheath. No new work or alteration should be considered complete until this labelling has been carried out and finally checked by an engineer. Where drawing-in boxes are not used, or the cable is laid direct, it is not possible to do more than label all joints.

Maintenance is considerably reduced if care is exercised in the original installation to ensure that cables are properly sup-

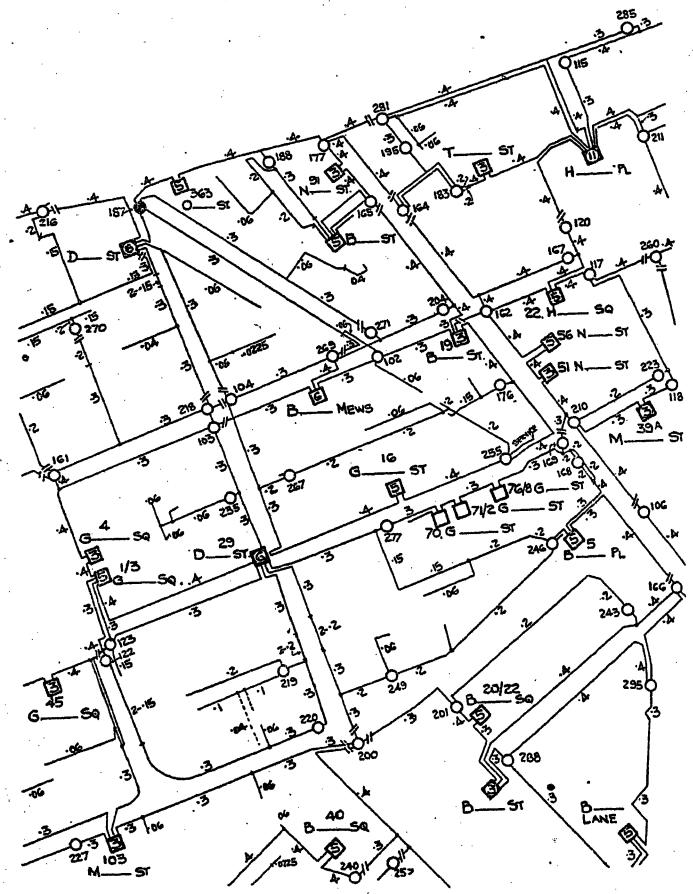


Fig. 8

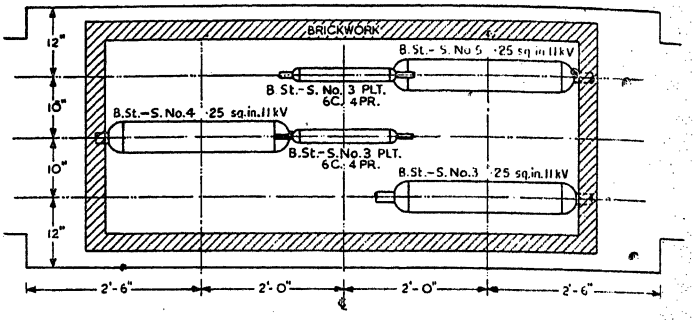


Fig. 10.—Details of standard joint hole on Street "B" to Substation "S" Nos. 3, 4 and 5 cable run.

straight joint or service tee, the continuity of the armouring is restored by bonding. Opinions differ as to whether the armouring should be plumbed on to the lead cable sheath, thus making sheath and armour a common conductor; or whether bonding should be carried out from armour to armour, with no contact between armouring and lead sheath.

On direct-laid systems it is desirable to have a reliable man on patrol in each district to observe that work carried out by other authorities does not interfere with, or cause damage to, the cables.

On multiple-duct routes where drawing-in boxes and inspection pits are installed, these should be regularly inspected to check undue presence of water or gas, the results being recorded in a card index (see Section 10.1). Ventilator grids should be cleared at the same time, but if these are of the grid type, set flush with street paving, it may be necessary to clear them more frequently. In order to prevent a leakage of gas from travelling any great distance through these routes, all ducts should be sealed on one side of each drawing-in box, so that each section of ducts is sealed at one end and open at the other.

Index	Street "B" to Substation "S," Feeder 5								
Section	Size (sq in)	Length (yd)	Date pulled	Drum No.	Make of cable	Joint	Colours	Jointer	Date
						End connect	St."B" [R.W.B / R.B.W] "S"	Smith	20.8.38
End connect To Joint 1	0·25	137·00	18.8.38	72/72164	B.I. plain lead	Joint 1	St."B" [R.B.W / B.W.R] "S"	Pilton	20.8.38
Joint 1 To Joint 2	0·25	217·67	27.7.38	63799	B.I. plain lead	Joint 2	St."B" [B.W.R / W.R.B] "S"	Elmes	28.7.38

Fig. 9

ported round the walls of drawing-in boxes and are led out of ducts in such a manner that the lead is not flattened on the mouths of the ducts. Much corrosion and subsequent damage has been caused by insufficient attention to this point, particularly where heavily loaded cables tend to "travel." Joints occurring in drawing-in boxes must also be properly supported.

Bonding will cause considerable trouble unless care is taken to ensure that it is sound mechanically. The only efficient method is to "plumb" the bond to the lead sheath of the cable.

Where armoured cable is drawn into ducts, or laid direct in the ground, it is important to ensure that, if the armour is removed for the purpose of making a

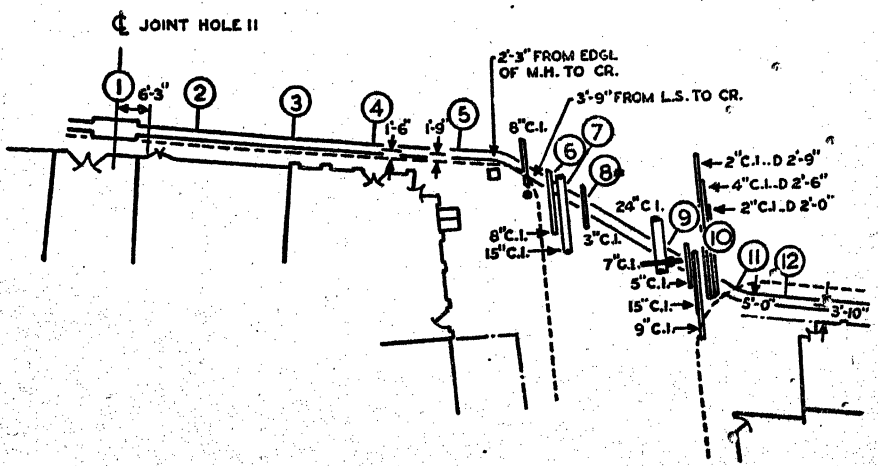


Fig. 11

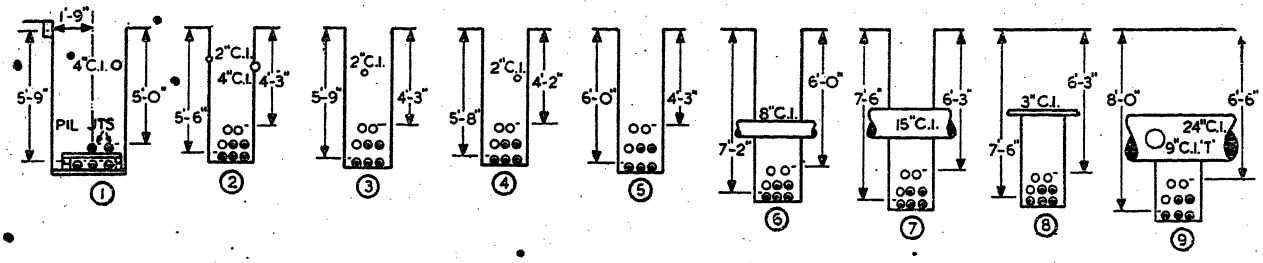


Fig. 12.—Cross-sections facing Street "B."

Cable data: 11 kV — *Route:* Avenue to D.D. Substation — *Compiled by:* T.V.B. — *Date:* 4.9.39 — *Sheet No.* 1

0·38 mile / Remarks	Section data: Actual length, yd: 0·075 sq in	Section data: Actual length, yd: 0·10 sq in	Section data: Equiv. length yd. 0·075 sq in	Section and Joint numbers	Joint data: Sketch Bk. Ref. Book	Joint data: Sketch Bk. Ref. Page	Joint data: Length from Avenue (yd) Actual	Joint data: Length from Avenue (yd) Equiv. 0·075 sq in	Joint data: Length from D.D. (yd) Actual	Joint data: Length from D.D. (yd) Equiv. 0·075 sq in	Position of joint hole
				End connection	24	33–34	—	—	675·66	613·83	Avenue substation
Plain lead, copper-screened	—	80·00	60·00	Section E.C.–1	24	57–58					
				Joint 1	24	34	80·00	60·00	595·66	553·80	Avenue, o/s No. 401
	—	64·33	48·24	Section 1–2	24	34–35					
				Joint 2	24	35	144·33	108·24	531·33	505·57	Avenue, o/s No. 383
	—	92·67	69·50	Section 2–3	24	35–37					
				Joint 3	24	37	237·00	177·75	438·66	436·06	"Y" Close, o/s No. 5–6
	—	10·33	7·74	Section 3–4	24	37					
				Joint 4	24	37	247·33	185·50	428·33	428·33	"Y" Close, o/s No. 3
Plain lead, unscreened	216·50	—	216·50	Section 4–5	24	37–39					
				Joint 5	24	40	463·83	402·00	211·83	211·83	Road "C," near main gate
	162·67	—	162·67	Section 5–6	24	42					
				Joint 6	24	59	626·50	564·66	49·16	49·16	Road "C," alleyway to substation
Single-wire armoured, hessian covered, in earthenware pipe	44·66	—	44·66	Section 6–7	24	59–60					
				Joint 7	24	—	671·16	609·32	4·50	4·50	D.D. substation cable race
Plain lead	4·50	—	4·50	Section 7–E.C.	24	—					
				End connection	24	—	675·66	613·83	—	—	D.D. substation

Fig. 13

Large drawing-in boxes and inspection pits should be kept as dry as possible and, if these are constructed of concrete, good results can be obtained by the use of waterproof cements; a 32-candle-power carbon lamp will assist in this, if combined with an adequate ventilating pipe.

Painting plain lead-covered cables with a bitumastic paint where they pass through damp drawing-in boxes will greatly assist in preventing corrosion. At the same time an inspection should be made of all bonding and plumbing of joints, especially where cables are known to be carrying heavy currents intermittently. Cable sheaths should be inspected for corrosion at the mouths of ducts.

Where duct routes are waterlogged there will almost certainly be impurities in the water. Any plain lead-covered cables should be watched to ascertain whether electrolytic action is taking place; this, of course, is possible only in drawing-in boxes. Where electrolysis is experienced, particularly if it is due to adjacent d.c. cables, the safeguard is to have a waterproofed duct run, i.e. a fibre or asbestos duct laid in concrete.

Far less damage by bombs has been caused to cables of the armoured type laid direct than to cables in duct routes. Armoured cables, up to 11 kV at least, have been found still working in bomb craters, apparently undamaged. It was not necessary to effect any repairs when the crater was filled, and no subsequent breakdown has occurred in a period of 2½ years. Broken ducts have caused much damage to cables of the plain lead-covered type or the plain lead type with a hessian serving. Joints have been cracked owing to cables being pulled along ducts by the force of explosions in bomb craters.

(10.3) Oil-filled Cable Maintenance

Oil-filled cables are becoming a more general feature of h.v. networks, and involve maintenance additional to that of the solid-type cable. The oil-filled cable system is dependent upon the satisfactory impregnation of the dielectric, which is achieved by dividing the route into sections fed by oil at a predetermined pressure. It is the maintenance of this condition that is the primary object.

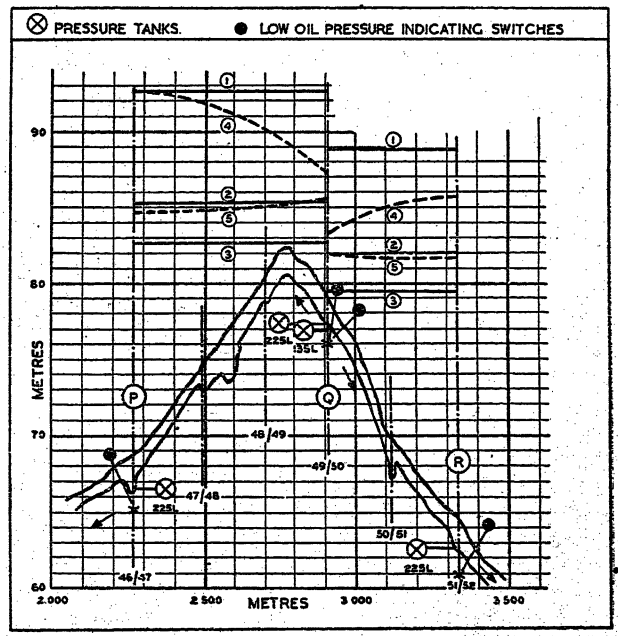


Fig. 14

1. Static head at full load, max. temp. 2. Static head at no load, min. temp. 3. Min. permissible static head. 4. Max. transient head. 5. Min. transient head.

Where oil-leakage alarm systems are installed, pressure readings at all feeding points, taken at intervals of 3 months, should be recorded and the load and temperature conditions noted. In taking these pressure readings, one gauge of suitable range should be used in preference to permanent gauges connected to each feed tank, as these are subject to corrosion and are liable to give false readings. The standard gauge should be periodically checked throughout its range.

Tabulation of the pressure readings may indicate small leaks. Dependent upon the magnitude of the leaks, losses of oil may be replaced by periodic pumping of the tanks until such time as location and repair of the leak can be effected. Such leaks, possibly caused by cracked or porous joint wipes, split lead sheaths or loose pipe connections, may prove extremely difficult to locate without extensive excavation and cost, and it may be expedient to extend the boosting of tanks until the leak attains such magnitude that location is more readily effected. If this is done, any indication given by the oil-leakage alarm will be due to serious loss of oil, which will require immediate attention to prevent complete loss of pressure in the cable section concerned. The admission of air into the cable or feeding apparatus must be prevented, but, where such has occurred, immediate treatment by flushing or circulating may obviate replacement.

The low or differential oil-pressure indicating switches should be tested over their operating range annually, and if the test results show any variation from those originally obtained the switches should be inspected. Such variation is usually due to excessive friction of the moving parts of the switch, which can readily be freed without alteration of the original settings. Where tank pits are subject to flooding, more frequent inspection of these points will be necessary to ensure that pumping is carried out, enabling work to be undertaken if required.

To enable the maintenance to be satisfactorily carried out, portable pumping and testing equipment must be available at all times, so that the lapse of time between indication of leakage and commencement of treatment may be reduced to a minimum.

(10.4) Feeder Pillars, Network Disconnecting-Boxes, etc.

These should be the subject of regular inspections, preferably not less than two a year, and should be painted with a black bitumastic paint (except possibly the outside of feeder pillars). Any h.v. disconnecting-boxes and ring-main units should have their diving-bell lids painted red as a ready means of identification and as a warning of danger. One method of identification is to allocate a serial number to each disconnecting box of whatever voltage, to paint this number on the lid of the box and also to insert metal figures in the concrete filling of the pavement cover. These numbers are recorded on the operation key maps (Fig. 8). Where the boxes are compound-filled the compound used should not set so hard as to crack even in the coldest weather, and any disturbance of the compound due to heat or water should be noted. All copper and brass contacts should receive a light coating of pure vaseline when the box is installed, and should be regularly inspected for corrosion.

Condensation may take place inside disconnecting boxes fitted with diving-bell covers, particularly at seasons of warm days and cold nights. This condensation can be considerably reduced if the inside of the diving-bell cover is coated with fairly large granulated cork, and, in very bad cases, by the addition of a piece of sarking felt laid on the top of the cover.

Free breathing should be allowed in disconnecting boxes, and the lip should not be filled with oil or vaseline.

Some trouble has been experienced with brass bolts due to fracture when these are used for securing contact on links; a solution has been found in the use of cadmium-copper bolts.

The earlier type of "phase barrier" in l.v. boxes, which were of teak, caused trouble by developing a fungoid growth. Various paint compounds were tried to overcome this difficulty and a remedy was found in Dr. Angus Smith's solution.

The more modern moulded-bakelite barrier has proved to be reasonably satisfactory. The only fault which has been noticed with this type of barrier is a slight elongation, producing a bowed side where the side is very long, which occasionally distorts the barrier unduly.

House service cut-outs are seldom inspected in the majority of undertakings, and while such inspection may be almost unnecessary where a modern type of bakelite cut-out fitted with h.r.c. or other dust-type fuse is installed, there are large numbers of the iron-clad type in existence. These should be inspected approximately every 3 years for rust and general corrosion of the iron box. Open-type fuses and earthing connections should be inspected and renewed if necessary.

(10.5) Standardization

Most undertakings have a variety of cable sizes and types, but it is desirable to reduce to a minimum the number of types and sizes used for all new extensions, and for replacements or reinforcements, depending on the type of distribution and density of load of the undertaking concerned. The authors suggest that for 11-kV cables the following sizes should satisfy all requirements: 0·04, 0·075, 0·15, 0·25 sq in. For intermediate voltages, as, for example, 3 kV in towns, one size only is suggested, namely 0·20 sq in for distributors, with, possibly, 0·10 sq in for h.v. services to small consumers' transformer chambers if these are arranged as a tee from a ring-main unit in the street. For 4-core medium-voltage cables, 0·10 and 0·20 sq in will be found suitable for all cases except in very dense areas. Residential properties of the suburban type can be served by one size only; the authors suggest 0·04-sq in twin cable, but if 0·0225-sq in is considered sufficiently large there should be no other size.

Maintenance is simplified if standardization on these lines is carried out. A further argument for standardization is afforded in that the different types of jointing, fitting, etc., are reduced to a minimum, thereby simplifying training and supervision of jointers. These remarks particularly apply to l.v. service jointing: the most suitable method for twin services taken off 4-core mains is the trouser or breeches joint. It has the advantage of requiring the minimum of width in the public path, the cores can be exposed to any desired length so as to avoid straining insulation at the crutch, and final mechanical protection is simple. An effective method for providing this protection is the use of three reinforced-concrete slabs, one being placed on each side of the joint and the space between slabs and joint filled with hard pitch, the covering slab being finally placed on top. This type of joint is suitable for all cored-cable tee joints, such as a 4-core from a 4-core.

Assuming that standardization of cables on as few sizes as possible is desirable, distribution engineers will lay down the standards for any particular undertaking.

It is of great assistance in identifying cables laid direct in the ground if a particular type of serving and armouring is allocated a particular voltage range, e.g. low voltage; 2 kV–3 kV; 11 kV; etc. If the range of servings is not sufficient for this it may be supplemented by further protection of a different sort; e.g. a 5in red concrete slab for 3 kV and a 7in for 11 kV.

Similar remarks apply to plant installed in the public highways, e.g. transformer pits and their contents, h.v. and l.v. ring-main units, disconnecting boxes, etc.; if a standard layout is adopted replacements of parts and general repairs are facilitated, and in rain and darkness location of the particular box required is made easy. The essential points of the maintenance programme are given in Table 5.

Table 5

ROUTINE INSPECTION OF MAINS

Type of plant	Interval	Work to be carried out
Drawing-in boxes, inspection pits, etc.	6 mth When necessary 6 mth	Inspect for gas and water Clear ventilator grids Inspect bondings and plumbing of joints Inspect cables for corrosion, paint with bitumastic paint in damp boxes or where corrosion occurs Inspect sealed ducts for gas-tightness
Oil-filled cables	3 mth 12 mth	Pressure readings at feeding points Test oil-pressure indicating switches
Disconnecting boxes, ring-main units, etc.	6 mth 12 mth	Inspect for corrosion, moisture, heating, etc. Paint all ironwork, including pathway frames and covers
House service cut-outs	3 yr	Inspect for rust or other corrosion of iron box Inspect fuses, and possibly renew if of open type Inspect earth connections

(11) CONCLUSION

It may be thought that in this paper the subject of maintenance has been approached with too much bias towards the design and layout of the initial installation. The authors have, however, endeavoured to show that maintenance, combined with adequate records, can foster improved design, to the mutual advantage of manufacturer and user, in order to obtain for future purposes the best design and layout practicable.

(12) ACKNOWLEDGMENTS

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DISCUSSION BEFORE THE TRANSMISSION SECTION, 10TH NOVEMBER, 1943

Mr. W. Casson: I believe that many of the major disasters with electrical plant have occurred owing to a combination of circumstances, one of which has been a defect that could have been detected by maintenance work or routine testing. Nevertheless, there are many engineers whose policy is to let the gear look after itself, and although they may in their period of office have no major breakdowns, their successors may have a very different experience. The result is often to swing the policy in the reverse direction, namely to over-maintain the gear, which is also an evil. The right policy can only be found after a period of years as a result of a careful examination of maintenance records, the cost involved, the effect of circuit outages and methods adopted. It is therefore very useful to obtain other people's experiences such as those presented in the present paper.

The Central Electricity Board's high figure of 92% correct operation of protective gear for the whole country for each of the last two years could only have been obtained by careful design and maintenance of all the gear involved. Much can be done by routine testing, particularly in tripping tests on circuit-breakers from protective relays, alarm tests and simple periodic inspections. In this connection I was very interested in the test equipment shown in Fig. 3. It is essential to have a scheme in which all items of test or inspection are listed, and there should be no chance of anything being overlooked or omitted. If tests or inspections cannot be carried out on the scheduled date, then the scheme should ensure that they are done at the first available opportunity after that date.

The paper deals only with cable systems and we should all welcome a similar paper on overhead systems, for it is generally impossible to have simple protective gear with these.

As regards busbar protection, I consider the replacement of auxiliary switches by hand-operated knife switches to be an improvement. An alarm feature is provided to ensure that the switches cannot be left in the wrong position.

Under feeder protection I note that tests on load are carried out periodically, and that when the balanced protection is temporarily cut out for this purpose the back-up over-current relays are set so as to afford complete protection. I do not propose to comment on the need for balanced protection if complete protection is afforded by over-current protection, but it is highly probable that the arbitrary rule of dividing the setting by two is applied, rather than deriving a setting after carrying out calculations of fault current on site and envisaging the type of fault which might occur.

I support the authors in their plea for greater co-operation between maintenance engineers and designers, not only of the gear but also of the network.

In conclusion, I should like to pay a tribute to the high standard of maintenance work outlined in the paper; although it may not be economically practicable for all supply authorities to carry out

this work in such a manner or to have the staff to deal with it, nevertheless it provides ideas for improvement and modification.

Mr. G. N. Wright: I consider the title of the paper to be very modest, as it contains so many useful suggestions regarding design and layout with a view to facilitating maintenance. There is much to be said in support of the authors' statement in Section 1 that it is an advantage for the staff responsible for maintenance to be also responsible for installation and, I would add, for choice of design. Failing this, it is essential that the departments concerned should work harmoniously together.

With regard to Section 6 and the acidity of transformer oil, the "safe" figure appears to be a very debatable one. Some years ago it was considered dangerous if 0·2 mg KOH per gramme of oil was reached. Later, up to 2·0 mg was considered safe. The figure of 1·0 mg recommended by the authors seems to be generally accepted by the industry at the present time.

In Section 7 the authors mention the trouble-free performance of hermetically-sealed transformers of comparatively small capacity. Is there any limit to the capacity for which hermetical sealing is possible, and, if so, is this due to economics or to design?

I agree that it is undesirable to use water fire-fighting installations for most types of indoor switchgear. Where the risk to be covered is of small value and dimensions, the cost of such an installation would be prohibitive, even if space could be found for it.

Mr. L. H. Welch: The importance of this subject is shown by the fact that the switchgear and cables concerned in Great Britain cost more then £300 million. A still more important aspect is that bad maintenance frequently leads to accidents involving injury and even loss of life. I am in almost complete agreement with the authors and believe that the various tables embody sound engineering practice, the details and figures given being more reliable than some of those issued recently in B.S. 1086 ("Maintenance of Electrical Switchgear") under the heading of "typical good practice." I doubt whether any supply undertaking takes samples of the oil in every switch tank once every 3 months, as suggested in this B.S. specification.

Rarely-operated switchgear in small chambers or on consumers' premises is frequently neglected. It offers a maintenance problem directly opposed to heavily-loaded and frequently-operated circuits, such as electric-furnace gear. Oil is the least stable element in control gear and switchgear to-day, and many would like to see equally-reliable enclosed apparatus avoiding the use of oil. I endorse the authors' remarks regarding cold purification of oil whenever possible.

The change in design of switchgear was very rapid before the war, so that most maintenance engineers are now faced with the problem of maintaining gear which is 10 or more years old and out of date. Many of the manufacturers' recommendations on maintenance are based on theoretical grounds; a good example of this is the use of heavy oil in isolating-switch chambers or busbar-selector chambers. All are agreed that these units require inspection, but the difficulty of handling the oil often means that there is a tendency to let well alone and neglect the work, or increase the period between overhauls to an undesirable extent. In short, the maintenance programme must be determined by the maintenance engineer; he, in turn, will only arrive at a reasonable and economic programme if he keeps careful records of the performance and maintenance of the apparatus. The authors rightly call for good records, and I should like to see added a complete system of fault reports, and by "fault" I mean any abnormal occurrence, however trivial.

Mr. H. C. Waters: I think the authors' statement regarding the use of the same staff for capital and revenue work needs qualifying. During intensive development periods, capital work sometimes assumes considerable proportions compared with routine maintenance of existing networks. In order to attain the highest efficiency in the utilization of labour, I have found it desirable to split the two sides, as it is generally necessary to regulate the maintenance staff in such a way that they work continuously to a predetermined programme, whilst it is easier to regulate fluctuations in labour requirements on the capital-works side. I agree, however, with the authors that when intensive development has been completed a combination of the two departments becomes essential.

As to safety precautions, the "permit-to-work" card system is a well-tried one, but it needs to be backed up by a good, simple, fixed code of working rules. In addition, having attended coroners' inquests following accidents, I have become very conscious of the need to keep a register of authorized and competent persons, which also prescribes the areas within which they may operate.

Period intervals for carrying out maintenance work have been suggested in Tables 1 and 2. With regard to switchgear, I think the amount of maintenance work economically necessary, and the interval period, need to be based upon a diagram showing the position of each switch relative to the source of supply and the follow-through fault current which can pass, together with information regarding the type and rated capacity of the switch itself. For, whilst it may be necessary frequently to overhaul a switch when installed near to the source of supply where the fault current is likely to be heavy, several openings under fault conditions and longer intervals between overhauls could be permitted at positions more remote. A diagram as suggested would enable switches to be zoned into categories of varying time-intervals for overhaul. Although I realize that after each switch opening under fault conditions it is desirable thoroughly to examine the switch where the load conditions are heavy, it is probable than this would be uneconomic in rural areas where long lengths of main provide relatively high impedance. Recently we have found it convenient to include in our maintenance schedule an extra item, which confirms examination of the winches lifting the oil tanks, as these now form equipment requiring periodic examination under the Factories Act. From the information so provided on the schedule a certificate is then made out in the office which is acceptable under that Act.

The authors have referred to periodic power-factor testing to ascertain deterioration of insulation, but I cannot see any reference made to the "Tebo" stick which we have found useful and simple to handle, particularly for insulators used outdoors.

Mr. H. C. Wells: I do not fully agree with the authors' remarks relating to the cold treatment and filtration of oil. I have had very satisfactory results with one type of apparatus which heats the oil, filters it, and finally drives off the moisture. I consider the testing of the acidity of the oil to be very important. Regular tests should be made at least every 12 months, and careful records kept with a view to ascertaining the rate of increase of acidity, if any.

With regard to oil-cooled transformers in underground chambers or pits, the undertaking with which I am associated has had very satisfactory service over many years from the hermetically-sealed type of transformer, and inspection has shown that there has been little or no deterioration of the oil.

With regard to switchgear and the use of busbar selectors, I think it depends very much on the position of the switch in the system and the number of times it is likely to require to be changed over, whether the oil-filled selector type or the plug type should be installed. Unless a switch is very frequently operated, I should always favour the plug type.

Many troubles have undoubtedly arisen with switchgear owing to the use of plugs and sockets on the auxiliary wiring connections. I think that switchgear makers should give every attention to this point and standardize, wherever possible, on some form of switch which will permit the movable portion to be moved without actual disconnection of the auxiliary wiring, except, of

course, where the switch has to be entirely taken away. If that were done, many failures would be avoided.

For small-transformer circuits, particularly in underground chambers, I think it would be desirable to omit automatic switchgear altogether, since modern transformers are usually much more reliable than are the cable systems supplying them. Such elimination of automatic switchgear would obviate many interruptions to supply resulting from lack of discrimination of protective apparatus and would save considerable maintenance cost.

As to fire-fighting apparatus, I think that gas equipment is in every way preferable for switch-houses where the use of water would be liable to affect other switches remote from the one which may be the cause of the fire. On the other hand, water protection is excellent for transformers and outdoor equipment.

I wish the authors could have given more information on the question of the bonding of cables and apparatus. A great deal of avoidable trouble has been caused in the past through lack of knowledge of the earth currents available at a given spot and the path they may take, and to inadequate bonding and the careless laying and crossing of cables, etc.

Years ago most undertakings used to pressure-test their high-voltage cables annually. Is this of any practical value?

The importance of standardization of cables, cut-outs, joint boxes, etc., must be stressed, and it is to be hoped that if the standardization of distribution voltages is made compulsory this will help in the maintenance of plant and gear.

Mr. J. Welford: In Section 4 the authors state that representative values of the flash-point of insulating oils should be taken infrequently and that they are not necessary for routine testing. I cannot agree with this statement. Other faults, such as those due to high acidity or low electric strength, are quickly reduced and isolated by the operation of automatic switchgear, but such protection is impotent against the explosion of a cracked oil. I agree that the cracking of insulating oil is a very rare occurrence, but the results of such faults are sufficiently serious to necessitate all precautions being taken. If the laboratory test is too tedious it should not be difficult to devise an apparatus to give an open flash test on site.

With regard to Section 6 on transformer tests, why need the insulation-resistance tests include cables, cable boxes and circuit spouts of switchgear? It is comparatively easy to disconnect the transformer windings from the cables, and specific readings for windings and cables separately would provide valuable information. If the transformer core is to be lifted for the examination of laminations, core bolts, etc., this disconnection cannot be avoided.

The record sheets illustrated in the paper seem to be lacking in detailed information. I am in favour of a separate card, not only for each unit, but also for each overhaul. Such a system has the advantage that it can be designed on a question-and-answer basis, so that no detail is overlooked; this ensures that the fitter indicates the results of his examination of each specific part. The final responsibility for all plant rests with the engineer, and test cards should therefore provide him with the fullest information and be so planned as to eliminate errors and oversights (and other very human fallibilities) on the part of fitters.

In Section 2 dealing with safety precautions, the authors do not mention the "permit-to-work" form given in the Standard Code of Practice, B.S. 1086.

The authors' remarks on close co-operation between the maintenance engineer and the designer cannot be too strongly emphasized, but I disagree with them that experience in a manufacturer's works should necessarily be gained by an engineer before he joins a supply undertaking. If this point were sustained from the angle of maintenance work only it might be tenable, but it must be remembered that supply engineering involves much which is outside the range of the manufacturer in civil and mechanical as well as in electrical engineering. It has moreover its own specialized corners in the fields of chemistry, combustion, administration, law and economics, and utilizes equipment not from one, but from many different manufacturers. A properly-organized training scheme in an efficient supply undertaking, coupled perhaps with occasional visits to manufacturers' works, can thus provide a training wider in scope and more relevant in detail to the sum-total of that knowledge which the supply engineer requires.

Mr. A. J. Gibbons: The criterion of satisfactory design of electrical plant is not so much what the designer thinks of it to-day but what the maintenance engineer will think of it in five years' time, and I support those who stress the importance of liaison between engineers responsible for specifying the layout and design of new work and the maintenance engineer. Manufacturers should be kept fully informed of maintenance experience so that design may be modified as necessary.

I agree entirely with the authors' comments on the superior merits of plug-change breakers, or, better still, change-over breaker equipments, on double-busbar metal-clad switchgear up to 33 kV. The saving of time attributed to oil-immersed change-over links is, in my opinion, illusory, since in any case I would prefer to have a breaker racked out before changing-over from one busbar to another.

The authors have hardly touched on the important subject of the earthing of metal-work and earth plates. I should be interested in their views as to the nature and frequency of the tests they consider necessary on earthing systems and earth plates.

The authors recommend a top oil temperature of 65° C for the "cut-in" point of forced-cooling plant on transformers. Would not the transformers run more efficiently if the cut-in point were higher and full advantage taken of the temperature limits laid down in B.S. 171? It is stated in the paper that with hermetically-sealed transformers oil temperatures as high as 80° C have not resulted in any trouble from sludge or acidity.

What would the authors recommend in the way of inspection should they find a transformer explosion-diaphragm ruptured? Have they had any experience of core-fault indicators?

The method described by the authors for carrying out capacitance tests on screened pilot cables is satisfactory and rapid, and requires a minimum of equipment, but the readings obtained are, of course, entirely arbitrary; it is essential that all tests be made with voltmeters having similar constants if the results are to be at all comparable.

The authors mention that the majority of faults on cables of 11 kV and less are caused by mechanical damage. I would certainly substitute 22 kV for 11 kV, and in 5 years' time I hope we shall be able to substitute 132 kV.

Mr. E. H. Jesty: It is stated in the summary that the paper refers only to "underground" networks. I think this word should have been included in the title. From the title as it stands, one might have expected a comparison of maintenance problems relating to underground and overhead networks, which would have been valuable.

There is one important matter which the authors do not even mention, namely the financial aspect of maintenance. It would have been enlightening to hear what proportion of the capital cost one might expect to spend annually on the maintenance of an oil-filled cable. It is generally agreed that a reduction in distribution costs is imperative if maximum development is to be achieved. Do the authors feel that such a reduction is likely to be assisted by spending less, or more, than is at present spent on maintenance?

Fig. 9 gives the length of a 0·25 in^2 11-kV cable between joints 1 and 2 as 217·67 yd. An accuracy of 0·07 yd, which is about 2½ in, represents about 1/30th of 1 per cent on that

length. I should like to know how this is achieved. Such accuracy cannot be attained by tape measurement or by the measurement of conductor resistance before jointing, since the jointer is likely to cut off more than 2½ in when butting the cores. To aim at such precision in assessing the length of each separate cable pull seems to me to be most uneconomic: and precision, like power-factor correction, becomes an expensive luxury if pushed to extreme limits.

In Section 10.2 the need is stressed of having a patrol-man on direct-laid systems. Such a man is equally necessary on duct routes. Unreported air-raid and other incidents are often detected by the patrol-man, and in consequence many incipient faults are prevented from developing.

I cannot agree with the authors' suggestion, in Section 10.4, of putting identification labels on the lids of disconnecting-boxes or of letting them into the filling of box covers. Serious consequences can follow the interchanging of covers and, although it sounds incredible, covers do get interchanged in the most unexpected manner. Once I found in south-east London a box cover labelled "Borough of Hammersmith Electricity Supply"; though I do not think that anyone was misled in that particular instance.

Mr. H. Lowe: The paper seems to me to contain too many elementary points: e.g. that particular care should be taken during overhaul not to introduce impurities into the oil by the use of cotton waste for tank cleaning.

I think that not only is it contradictory to speak of maintenance staffs carrying out both capital and revenue work, but also that the maintenance staffs are of an entirely different temperament from the constructional staffs, and that they should be chosen with that in mind.

In Section 7 mention is made of the design of substation buildings. Is it not for engineers to demand what they need rather than to let the architect give them either what he thinks suitable or can best spare, and which is often most unsuitable for its purpose?

I realize that the paper does not refer to rural areas, but the authors suggest in Section 10.5 certain sizes of cables which they think should satisfy all requirements. In my opinion these do not go low enough. In the same Section, concerning l.v. service jointing, they say that the most suitable method for twin services taken off 4-core mains is the trouser or breeches joint. I think that requires much more justification than they offer.

Mr. F. H. Pulvermacher: Have the authors had any experience of low-voltage re-wirable fuses? In the undertaking with which I am associated the custom is to carry out inspections twice a year and re-wire where necessary. Do the authors consider that one single wire is preferable to several of a smaller size? I admire the extremely detailed record card which they include, and which puts my own to shame. I have found a log-book very helpful, containing simply the bare dates and a brief summary of the work carried out at all substations.

If public lighting is not outside their scope, what sort of maintenance do the authors give lamps and chokes on mercury-discharge lighting where this has been out of use since the beginning of the war?

Mr. A. W. Allwood (*communicated*): While it may be true that in many undertakings, particularly those entirely urban in character, it is not possible to find continuous employment for a separate staff for new construction, in an undertaking engaged in developing a large rural area a separate constructional staff could be kept fully employed. Providing there is a close liaison between the constructional and maintenance staffs, there are many advantages to be gained by this arrangement. First, increases in construction costs, caused by suspension of work owing to labour being diverted to deal with breakdowns, are avoided, and secondly, there is less tendency for maintenance to be neglected in favour of constructional work.

With reference to staff training, I am not sure that works experience is necessary for all staff members. The practical ability of a trainee may be equally well developed on a supply undertaking, with the advantage that he is, at the same time, gaining a valuable knowledge of supply engineering. On the other hand, works training, which specializes mainly in production methods, may occupy two or three years after graduation at a university, with the result that the young recruit to the supply industry may reach about 24 years of age before attaining his first junior position in which he will require to learn the practical details of supply engineering. I would make an exception in the case of testing engineers, for whom training in a works laboratory is of undoubted advantage. In the case of jointers, there is a real danger that if they are trained on the undertaking, obsolete methods will be perpetuated. To avoid this, the foreman jointer should be trained by a good cable-making firm and should periodically return for instruction in new methods.

I am glad the authors emphasize the necessity of noting relay signals after fault operation. It is surprising how little importance is attached by some mains engineers to such records; operators must be trained to make a complete record of all relay operations.

Presumably owing to the nature of the undertakings with which they are associated, the authors have said nothing about the maintenance of overhead lines. This matter is of obvious importance on rural networks. The main essentials are: a regular system of line patrols reporting matters requiring attention, arrangements with the distribution engineer for the isolation of parts of the network on which work has to be carried out, and the replacement or repair of equipment showing signs of damage or incipient failure. Tree trimming is also of importance in preventing unnecessary interruption of supply.

Finally, I should like to endorse the authors' plea for standardization. Many undertakings use far too great a variety of sizes and types of cables, joints, insulators, etc. The Norwich Corporation undertaking, with which I am associated, has recently reduced the number of sizes of cable used to about a third of those formerly stocked, and is reviewing the whole range of distribution accessories with a view to standardizing on the minimum possible number of different sizes and types. The saving in stores alone is well worth the trouble involved, and it is anticipated that the financial and technical advantages will be considerable.

Mr. E. A. Burton (*communicated*): The authors do not mention Buchholz protectors when dealing with either transformers or protective gear. The size and importance of some of the transformers mentioned in the paper would appear to justify the fitting of these devices. If this is so it would be of interest to know the experience of the authors with the apparently simple "gas accumulation" function. What method do they use for collecting the gas, and have they any yardstick for the interpretation of the results of chemical analysis of the gas?

The initial fitting of the protectors very often appears to be more in the nature of an afterthought, the protector being adapted to suit the pipework, rather than the pipework and tank cover to suit the functions of the protector. Forced oil-cooling, too, is sometimes not co-ordinated with the protectors and the design of its pipework. Have the authors developed a standard code for protector pipework? What are their views on explosion vents on transformers, particularly where Buchholz protectors are fitted?

Winding-temperature thermometers are not mentioned. What, if any, is the authors' experience with these instruments?

From Section 4.1 the importance of adequate heating and ventilation in switch-houses is realized. The provision of thermometers is not uncommon in switch-houses. Unfortunately, however, personnel are not so sensitive to high humidity as they are to low (and high) temperatures, and very

often the dew-point is the only warning that high humidity conditions exist. In the more important switchgear installations, some form of hygrometer, either of the indicating or recording type, would be a truer guide to the maintenance engineer of the effectiveness of the heating and ventilating arrangements.

Mr. J. L. Carr (*communicated*): The necessity for careful organization for maintenance and control of extensive electric-supply systems cannot be overstressed, and the method outlined of placing mains and substations under common control presents advantages in preventing overlapping and facilitating attention to local interruptions.

Attention is drawn to the necessity for heating and ventilating substations adequately. It does, however, seem inefficient to dissipate heat from transformer chambers into the air, and then install electric heaters in the adjoining switch-room. Fire precautions naturally prevent interchange of air between the compartments; but, with adequate precautions, it should not be beyond the ability of the substation designer to improve on the present position.

In discussing transformer oils, the authors' statement that Grade "A" oil releases its acid content is unfortunate and inaccurate. Acid is an oxidation product and is not actually present initially; under suitable conditions, its formation may, to a large extent, be prevented. The fact that outdoor transformers are less prone to develop acidity is principally due to constructional features which reduce the probability of oxidation and the ingress of moisture; improved cooling facilities also contribute by reducing the temperature. The use of conservators has other advantages, namely in reducing the possibility of flash-over at the terminals and the firing of explosive gas mixture in the tank in consequence. At least one disastrous fire reported some years ago had its origin in this way. With conservators, also, sensitive gas detection is possible; the normal electrical protective arrangements adopted for transformers are at a disadvantage in this respect. I consider that much greater use of transformers fitted with conservators is desirable in future, particularly at points where fire risks are most important. Attention is drawn to a recently-published report of the E.R.A. on oil acidity.

Too much attention may be paid to routine insulation-resistance tests, particularly as regards cables. Regular tests over a period of years on one h.v. system disclosed only one or two incipient faults, and the expense and inconvenience were not warranted. Commissioning tests on protective gear are most important: in the past, protective arrangements have frequently been condemned because of inattention to careful installation and subsequent maintenance.

It is surprising to learn that much corrosion has occurred at duct mouths in draw-in boxes; mechanical damage and abrasion has undoubtedly occurred, particularly in heavily-loaded duct lines.

Standardization of a minimum number of cable sizes deserves full support. For high voltage we use 3-core cables of 0·3 and 0·15 in^2; for medium voltage, 4-core cables of 0·5, 0·3, 0·2, 0·1 in^2, generally, the second predominating; but for 4-core services smaller sizes are used. This simplifies stocking and replacements.

Mr. J. S. Forrest (*communicated*): This paper should do much to encourage power-supply engineers to adopt more comprehensive and rational maintenance methods.

In Section 2, the authors discuss safety precautions, and I fully agree that live-conductor detectors should be used before applying an earth connection to cellular switchgear. These detectors might also be used with advantage on metal-clad switchgear, particularly when it is necessary to apply the earth connections by hand.

With reference to Section 4, it is usually convenient to combine the testing of switchgear insulation with the annual maintenance, and in the case of outdoor switchgear both maintenance work and insulation testing should be done during the summer. A satisfactory insulation test for routine use is the measurement of insulation resistance at a reasonably high voltage, say 5 000-V d.c. Such a test will detect practically all the forms of insulation deterioration experienced in practice, and faulty bushings and switchgear operating-rods have often been located in this way. The insulation-resistance test can be carried out by the ordinary routine-maintenance staff, and specialized technical personnel need only be consulted in borderline or obscure cases. A further advantage of this method of test is that the test equipment can be made safe to operate; this is an important consideration when an extensive testing programme is contemplated.

In Section 4.7, the authors express a preference for permanent connections in flexible tubing between the circuit-breaker and the fixed portion of the switchgear. I should like to see this arrangement adopted universally.

Regarding Section 6.1.2, it is worth remarking that it has been possible, in general, to maintain an acid value not exceeding 0·2 mg per gramme for Class "B" oil in large outdoor transformers. It is now considered that one of the best criteria of the condition of an insulating oil is its power factor, but the power-factor test is seldom used as a routine-maintenance test, as some form of bridge circuit is required to make the measurement. The resistivity of transformer oil, however, is inversely proportional to its power factor, and thus forms an equally good criterion of the condition of the oil; it can be measured by relatively simple apparatus. This test is tending to replace, or at least to supplement, the usual breakdown-voltage test.

I strongly support the authors' plea for the standardization of switchgear, transformers and cables; such standardization should apply not only to the equipment as a whole, but also to component parts such as bushings and cable boxes. In general, any two items of equipment which perform the same function should be interchangeable.

The authors make no reference to routine cable testing. Do they consider d.c. pressure tests on cables effective for minimizing failures in service?

Mr. G. W. E. Gray (*communicated*): Section 1 dealing with staffing is an all-important one. I suggest that there should be very little difficulty in post-war years of appointing Chartered Electrical Engineers to the senior and senior-assistant posts, both technical and administrative. Fitter and maintenance staff should undoubtedly be trained in manufacturing shops and also be given every opportunity to carry out both revenue and capital works. Employment of jointers and their mates on substation-plant maintenance, as practised in some undertakings, is totally wrong.

Section 2 makes no mention of the procedure adopted by the authors' undertakings when isolating and earthing h.v. apparatus. Have the authors adopted the neon-tube test before earthing, and if so what is their opinion of its usefulness?

Section 3 deals very comprehensively with record systems. Records with particular reference to substation plant are essential, but one often finds difficulty in maintaining these, except where a specific records clerk is employed. I suggest below a method which should enable a substation engineer and his assistant to keep records posted to date. A daily log-book is kept, in which detailed daily records are made of all work and tests carried out, etc. These are then posted to record sheets or cards as shown below. Other sheets or cards are suitably drawn up for: "General Lay-out of each Substation," "General Data," "Switchgear Data," and "Transformer Data," etc.

Sections 4 and 6 refer to very important factors, but routine maintenance is invariably difficult to ensure. A good motto is "To do all the good you can to all the plant you can whenever it is available." When designing the network the extra capital cost involved to provide for adequate interconnection of systems, thus enabling substations to be totally isolated for reasonably indefinite periods, should not be too readily regarded as unprofitable.

SWITCHGEAR OVERHAUL

Substation		Switch Unit			
Date	Remarks	Oil	Trip Tests	Ref.	Insp.
8–12–43	Overhaul	30 kV B.D.V.	O.K.	A/150	G.W.G.

TRANSFORMER OVERHAUL

Substation			Maker	No.	etc.
Date	Oil		Remarks	Ref.	Insp.
	Acidity	Dielectric			
6–12–43	1·5 mg	30 kV B.D.V.	Inspected	A/127	G.W.G.

Mr. T. Kearns (*communicated*): I would endorse the statement that "sufficient attention is not always given to bold and conspicuous labelling," having in mind a near escape due to a bank of h.v. cubicle-switches being labelled only at the switch handles and not at the cable-entry positions at the back of the cubicles, where most of the handling of bare conductors takes place. The labelling of l.v. switchgear often starts in great detail, but falls into disuse owing to the impracticability of keeping up to date with frequent network alterations; this is particularly the case with distribution networks not incorporating feeder cables, where the best method is to number the various l.v. switches and fuses. Identification is of great moment to maintenance work if there is to be no undue interference with supply. Part of the paper might with advantage have been devoted to the question of the bearing of maintenance on interference with supply. An exact knowledge of network loadings, also, is essential to enable awkward maintenance problems to be overcome, particularly with consumers requiring a full 24-hour supply.

The authors state that for operational purposes on the l.v. network a key map is constructed on a "geographical basis." Presumably this means on the basis of Ordnance Survey Sheets; whilst this is essential for development purposes, I suggest that for operational work a record for each substation should be constructed on a diagrammatical basis, showing cable distances to adjacent substations. Such record sheets are incomplete if they do not furnish the latest maximum loadings, as well as the spare supply capacity available at the substations. The authors also state that the operational key maps should be kept up to date on a "daily basis." Surely it is not intended that sectionalizing records are satisfactory if correct to within 24 hours. So many of the staff (not conversant with current directions of the control engineer) are affected by "breaking points."

In practice I have found the following method to be best. The l.v. operational diagrams are quadrupled; the first set placed in the control engineer's office, the second in the emergency engineer's office, the third distributed throughout all substations, and the fourth (a "mobile" set) placed in the drawing office. The chief control engineer gives instructions for network alterations to the operating engineer, with prior information to the drawing office. The operating engineer takes the control and emergency sheets to the drawing office, where he is supplied with the altered "mobile" sheet. Before the work is effected, the engineer removes the sheet from the substation concerned, and replaces it with the corrected mobile sheet after the work has been done according to plan. The absence of this record indicates that alterations are in progress—even though of a temporary nature—and care must therefore be exercised. H.V. procedure is on similar lines, except that sheets at substations would require too much attention, and small diagram books are issued instead to the operating staff.

Mr. R. A. York (*communicated*): The authors state that periodic insulation tests are made on transformer windings, and yet no mention is made of insulation tests, using either a high-voltage test set or a Megger tester, on high-voltage or low-voltage cables. I have found that such tests on high-voltage cables using only a Megger tester are very useful in tracing incipient faults. I consider the need for these tests much greater on cables than on transformers.

In Section 10.4 it is stated that all boxes must be allowed free breathing and that any lips on diving-bell lids should not be sealed. I disagree with this as I have found that the condition of both high- and low-voltage boxes has been much improved by sealing diving-bell lids. All troubles due to condensation and to water getting into boxes have been eliminated, even in situations where a large head of water exists on the box.

The paper does not state the highest-voltage network on which street boxes are used and at what voltage link alterations are made on live boxes.

The authors make no mention of either earthing or cable-fault location. I should be interested to know whether any tests are made previous to installing any earth electrode, what earth resistances are generally obtained, and whether any subsequent testing of earth resistances is carried out.

It appears from the sample cable card, which gives equivalent lengths of cable for one size, that the Murray loop-test is the main method of fault location. For faults consisting of short circuits between cores, or between two or more cores to earth, with or without open circuit, on cables up to 10 miles long and up to 11 kV, I have found that an induction method is much quicker than the Murray test. It can be carried out without removal of consumers' fuses, and is extremely reliable. The method can be extended to short-circuits from one core to earth if isolation of the cable earths is possible. I should be interested to hear if the authors have had any experience with a similar method.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. F. N. Beaumont and **F. A. Geary** (*in reply*): Although general agreement is expressed on the necessity of close co-operation between maintenance engineers and designers and on the question of standardization, there is some cleavage regarding construction and maintenance being handled by the same staff. As Mr. Waters points out, the desirability of separate staffs is a question of the size of the undertaking and the development work in hand, but co-operation between them is essential; we agree with Mr. Wright's summing up and with Mr. Allwood's remarks; we disagree with Mr. Lowe that temperament is a consideration. Mr. Gray's point that the network should be laid out so that plant may be made available for routine maintenance is most important.

Regarding the routine pressure testing of cables raised by Messrs. Wells and Forrest, we think that a high-voltage d.c. test, apart from the commissioning test, is unnecessary if there is reason to believe that the network under review is normally sound and that these tests are, in practice, productive of faults. Mr. York's insulation test is useful where concentric cables with an earthed "outer" are used, and we agree with Mr. Carr on this subject.

Replies to points of Individual Interest.

Mr. Casson.—The object of the reduced setting of the over-current relays during on-load tests on balanced schemes is to ensure that an internal fault will be quickly cleared by a normal back-up feature

without jeopardizing the continuity of parallel supplies. We consider that over-maintenance is an uneconomical policy rather than an evil, but maintenance should err on the liberal side.

Mr. Wright and Mr. Welch.—We agree entirely with their views. Hermetically-sealed transformers up to 2 000-kVA capacity are in use; the governing factor appears to be a mechanical one. If applied to a unit with forced cooling the circulating system would have to be sealed from air intake.

Mr. Waters.—We agree that the "permit-to-work" card system must be backed by a rigid code of regulations. In our undertakings a register of authorized persons is kept with the co-operation of the control departments.

We do not agree that it is necessary to differentiate between switchgear near and remote from power stations; mechanisms on infrequently operated breakers require equal maintenance to ensure reliable operation. In accordance with the Factory Act all our lifting tackle, switch trucks, etc., are periodically overhauled at an approved testing station.

Mr. Wells.—If preheating of the oil causes any impurities to dissolve, they will pass through the filter in the dissolved state; cold filtration is therefore favoured, particularly in dealing with transformer oils, in view of the relatively low temperature at which sludge dissolves. A type of flexible tubing for small wiring on switchgear in which a plug box is screwed to the breaker unit and which can be disconnected if the breaker has to be entirely removed, appears a satisfactory arrangement.

We agree that in practice far too little consideration has been given to the bonding of cables and apparatus. Adequate thermal capacity must be provided to carry calculated possible fault currents without damage to the lead sheaths of adjacent cables, etc.

Mr. Welford.—The remarks in Section 6.2.1 on the "cracking" of oil also apply to switchgear. We fail to see the reason for disconnecting cables from transformers for routine insulation tests: it is not necessary to test individual components unless a divergence from previous test figures is noted. We contend that only essential items of maintenance should be recorded; no record system, however detailed, will compensate for poor workmanship and training. The "permit-to-work" card used in our undertakings embodies the same information as that in B.S. 1086. The average supply company affords little opportunity for a student to obtain that basic workshop and construction knowledge which is essential in engineering education.

Mr. Gibbons.—Apart from the initial tests on earth plates, we recommend routine tests every three years; all bonding and earth-bar connections should be inspected during the routine overhaul of plant. The figure of 65° C top oil temperature for the "cut-in" point of forced-cooling plant is based on excessive sludging found in several units on the original setting of 80° C.

Deterioration of bakelized-linen explosive diaphragms has been found; we would be guided by the kind of fracture and evidence of oil-throwing before deciding the nature of inspection necessary. Diaphragms are not fitted to hermetically-sealed types, but distortion and fracture of the bellows may result from excessive internal pressure.

Core-fault indicators, based on the principle that a core fault causes a variation in the flux distribution, have been devised, but we have no direct experience of these instruments.

Mr. Jesty.—The financial aspect of maintenance is beyond the scope of the paper, but the ideal is the minimum cost consistent with continuity and reliability of supply, and this must therefore determine whether less or more should be spent than at present on maintenance in any particular undertaking.

The accuracy in measuring cable sections was obtained by actual tape measurement. Since a long cable run includes many such sections, this accuracy is justified in arriving at a total length for such purposes as the Murray loop test.

Mr. Lowe.—The suggestion that engineers should demand from architects what they need is not productive of good results in our experience. The sizes of cables suggested in Section 10.5 cover those needed for an urban area; obviously they will not be suitable for all areas, but a minimum number of cable sizes should be used.

The suggestion that the "trousers" type of joint for services taken off low-voltage mains requires more justification than that given in Section 10.5 is difficult to understand; we know of no other type of joint embodying all the facilities mentioned.

Mr. Pulvermacher.—Low-voltage re-wirable fuses of the h.r.c. type are used in one of the authors' undertakings and have given satisfactory service. In practice they are seldom, if ever, re-wired, as it is cheaper and quicker to put in a complete new fuse.

We did not refer to public lighting. Most of the chokes on mercury-discharge lighting have been removed since the start of the war, as the insulation resistance was becoming very low, although some were left in commission and show no apparent deterioration.

Mr. Allwood.—Assuming that a student completes his college training at 21 years of age and then enters one of the excellent apprentice-training schemes of the larger manufacturers, we believe his basic engineering knowledge at 24 years is wider than would be obtained by entering a supply company on leaving college.

Mr. Burton.—Buchholz protectors are referred to in Table 4 and are used on large units; alarm float and flap types mounted in the straight bus pipe, inclined at the recommended angle, between conservator and transformer tank, give good results. Detailed inspection is desirable after the operation of the alarm float if the gas is combustible. The performance of explosion diaphragms is doubtful; in one instance the transformer tank was fractured, leaving an intact diaphragm. Winding-temperature instruments are briefly referred to in Table 2; trouble from leakage of volatile liquid has been experienced. One London undertaking installs separate electrically-operated oil-temperature indicators on each transformer control panel to give a check on the performance of the cooling plant controlled by the winding-temperature instrument. We agree that a form of hygrometer is desirable in situations where very high humidity exists.

Mr. Carr.—We endorse the desirability of having conservators on transformers; the exclusion of oxygen is responsible for the low acidity and sludge content of the oil in hermetically-sealed units. We confirm that corrosion does actually occur at duct mouths in "drawing-in" boxes.

Mr. Forrest.—The approved method of earthing on metal-clad switchgear at our undertakings is to apply the initial earth connection through an automatic oil circuit-breaker after the remote end has been isolated and locked off; working earths are afterwards applied where necessary. Detectors are not used on metal-clad equipment. We deprecate the "flashing" of spouts on metal-clad switchgear using an earthed cable.

Mr. Gray.—Record cards of plant maintenance are filled in after each overhaul, and a daily log-book is kept for all operations.

Mr. Kearns.—The procedure advocated with regard to operational diagrams seems rather complicated and is unusual, in that a chief control engineer is responsible for l.v. network alterations, usually the function of the distribution engineer.

Mr. York.—We have had far less trouble on disconnecting boxes with free breathing than on those in which the lids are sealed. The highest voltages on which street boxes are used, and alterations to links made live, are 3-kV single-phase and 3·3-kV 3-phase.

Earth-plate resistances vary; an average is 0·25 ohm, but figures of the order of 0·01 ohm are obtained.

We are very interested in the statement that faults on l.v. mains can be localized without removing consumers' fuses, by the induction method of testing. We have used this method for h.v. feeders only.

EMERGENCY LIGHTING SYSTEMS AND THEIR APPLICATIONS, WITH PARTICULAR REFERENCE TO BATTERY EQUIPMENTS*

By S. H. CHASE, Associate Member.†

(*The paper was first received 27th May, and in revised form 27th August*, 1943. *It was read before the* INSTALLATIONS SECTION *11th November*, 1943.)

SUMMARY

In recent years there has been an increasing call for the installation of emergency—sometimes termed "alternative" or "secondary"—lighting systems. These can be provided by candles or nightlights, gas, dry- or wet-battery torches, accumulators, engine-generator sets, alternative independent mains supply, or by a combination of several methods. The amount of emergency lighting may range from an intensity equal to normal down to the minimum considered necessary for safety and continuation of essential services. This paper deals mainly with the use of accumulators for standby purposes, operated either manually or automatically upon failure of the mains supply and capable of supplying loads for varying periods according to the class of installations, which are grouped under five heads.

(1) THEATRES AND CINEMAS

(1.1) Historical

The Theatres Act of 1843 enacted that a licence must be obtained from the Lord Chamberlain or from the Justices of the Peace of the County (this power was later transferred to County Councils under the Local Government Act of 1888) before any premises could be used for the public performance of stage plays, but the earliest demand for the provision of an alternative source of lighting was probably that which followed the passing of the Metropolis Management and Building Acts Amendment Act of 1878, and similar Acts covering other parts of England. This Act empowered the local authority to make regulations governing the structural arrangements and equipment of any theatre or other place of public resort, and made it unlawful to open or keep open any such premises except in pursuance of a licence granted by the Lord Chamberlain or the local authority, and before such premises were used under any such licence they had to conform to those regulations.

The regulations issued by the various authorities have, of course, been amended and amplified since that date, and now also cover premises kept for public exhibitions, dancing, music and other public entertainments of the like kind, and sometimes public boxing or wrestling contests.

The issue of Regulations dated 30th July, 1923, by the Home Secretary, under the Cinematograph Act, 1909, applying to all buildings used for cinematograph exhibitions, still further added to the responsibilities of the local authorities.

(1.2) Regulations—Local Authorities

Local authorities now issue one set of regulations which apply to any theatre, cinema or other premises under their jurisdiction covered by the Acts, and although these are now based on the Home Office Regulations, with which they have to comply, there is no uniformity.

There are, however, a number of requirements as regards the secondary lighting equipment which are common to most of these regulations, and it will be helpful, before describing the various types of equipment, if the more important of these are referred to as follows:—

(*a*) Detailed specifications and drawings of the proposed scheme to be submitted before the commencement of the erection or adaptation of the premises, these to be fully considered and amended, if necessary, before approval, and later to form the record of the work.

(*b*) All portions of the premises to which the public have access shall be provided with two independent systems of lighting.

(*c*) The lighting has to be maintained continuously the whole time the public are on the premises, and on neither of the two systems must the degree of lighting be less than is sufficient to enable the public to see their way out of the building at any time.

(*d*) Each system of lighting has to be such that a fault or accident on one system cannot in any circumstances affect the other.

(*e*) Change-over switches or other arrangements by which all or any part of the minimum lighting can be transferred from one system to the other shall not be provided. (This condition has been modified and is referred to later.)

(*f*) Exit signs may be illuminated by a light on either system, the lighting of which must not in any circumstances be extinguished or dimmed while the public are on the premises.

(*g*) Corridors and staircases which form the means of escape from the stage or platform and dressing rooms, and the notices indicating the exit signs from such portions of the premises, shall be provided with two independent systems of lighting.

(*h*) The secondary lighting battery shall be installed in an enclosure of adequate size and be constructed of fireproof material, and shall be ventilated to the open air. It shall be charged before the admission of the public to such an extent that it is capable of maintaining the full secondary lighting load for at least 12 consecutive hours. It shall not be charged whilst the public are on the premises.

Alternatively, the secondary lighting may be supplied by a battery in parallel with a convertor, provided it is run during the whole time the public are on the premises, and a pilot lamp or lamps shall be provided to show that the convertor is operating. The capacity of the battery must be such that it will supply the whole of the safety lighting for at least 3 consecutive hours. It shall be fully charged before the admission of the public, and the circuit shall be such that the battery cannot discharge through the convertor. When the battery is discharged to two-thirds of its capacity, the public shall leave the premises and shall not be re-admitted until the supply from the convertor is resumed and the battery is fully charged.

(*j*) The electrical installation shall be in the charge of a competent person during the whole time the public are on the premises, and a certificate by a qualified electrical engineer to the effect that the whole electrical installation has been examined and tested and is in safe working condition shall be submitted once every 14 months.

(*k*) Some authorities also make it a condition of the issue of a licence that the secondary lighting equipment shall be inspected and tested quarterly by a competent battery inspector.

(1.3) Alternative Public Supply

Where it is possible to obtain for secondary lighting purposes an electric supply from a source entirely separate from that of the primary lighting, and where a suitable tariff can be arranged, the scheme has advantages over other forms of secondary lighting

* Installations Section paper.

† Chloride Electrical Storage Co., Ltd.

because in the event of a failure of the primary supply the public can remain in the building until the primary supply is resumed, and no special secondary lighting equipment is required. Separate enclosures must be provided, however, for the switches, meters, etc., of the two supplies, each enclosure being illuminated by both systems. The enclosures must be constructed of fire-proof materials, and must be in a dry position and ventilated to the open air.

(1.4) Charge and Discharge of Battery

The secondary source has to be available during the whole time the public are in occupation of the building, and if a battery is employed to provide the secondary lighting its capacity must be sufficient to supply the secondary lighting for as long as 12 hours. As the battery must not be on charge during the performance, it is a problem to decide how the battery, which has been on discharge for this time, can be recharged. In any event the daily discharge, followed by the necessary recharge of the battery, causes inevitable wear and tear on the plates and the expense of their renewal from time to time. Also, to obtain the best results from the battery, the attendance of the person responsible for the charging is required at times when the premises would otherwise be closed.

(1.5) Floating-Battery Equipments

An arrangement which avoids the daily discharge, allows a smaller-capacity battery (3-hour) to be employed, and at the same time provides adequate protection for the public, is the floating-battery equipment, and this is now the generally accepted practice.

(1.5.1) Motor-Generator Sets.

A typical equipment consists of the motor-generator set shown in Fig. 1, the battery being of sufficient capacity to supply the emergency lighting for 3 hours. Pilot lights are provided to the requirements of the local authority concerned, to indicate whether the normal floating conditions are obtaining or whether the battery is itself supplying the lights.

The generator output has to be such that it will (1) adequately supply the full secondary lighting load (at least one authority requires a capacity 25% in excess of the total load), and (2) have a voltage range, with the series winding short-circuited, which will fully recharge the battery after an emergency discharge.

The generator, being compound-wound, supplies the whole secondary lighting load through two reverse-current and overload circuit-breakers, the voltage being adjusted until the centre-zero ammeter reads slightly on the "charge" side, to ensure that the battery, under normal floating conditions, is kept as far as possible in a fully charged condition.

A voltage of approximately 2·1 volts per cell has therefore to be applied to the battery, and the number of cells usually employed on a floating scheme has to be that number which will enable this to be done, i.e. 48 cells for a 100-volt circuit and *pro rata*.

It follows that the voltage of the battery, when called upon to discharge, must necessarily be lower than that of the floating combination, and on the 100-volt circuit will be no more than 96 volts even at the commencement of the discharge.

If the supply to the motor fails, the battery remains connected to the load, the reverse-current circuit-breaker preventing a discharge back to the generator and isolating this from the remainder of the circuit. Otherwise, and especially if the motor is driven by an a.c. supply, the speed of the motor-generator set remains substantially constant, and by using a level compound-wound generator with close regulation the battery can be floated to give a number of years of satisfactory service.

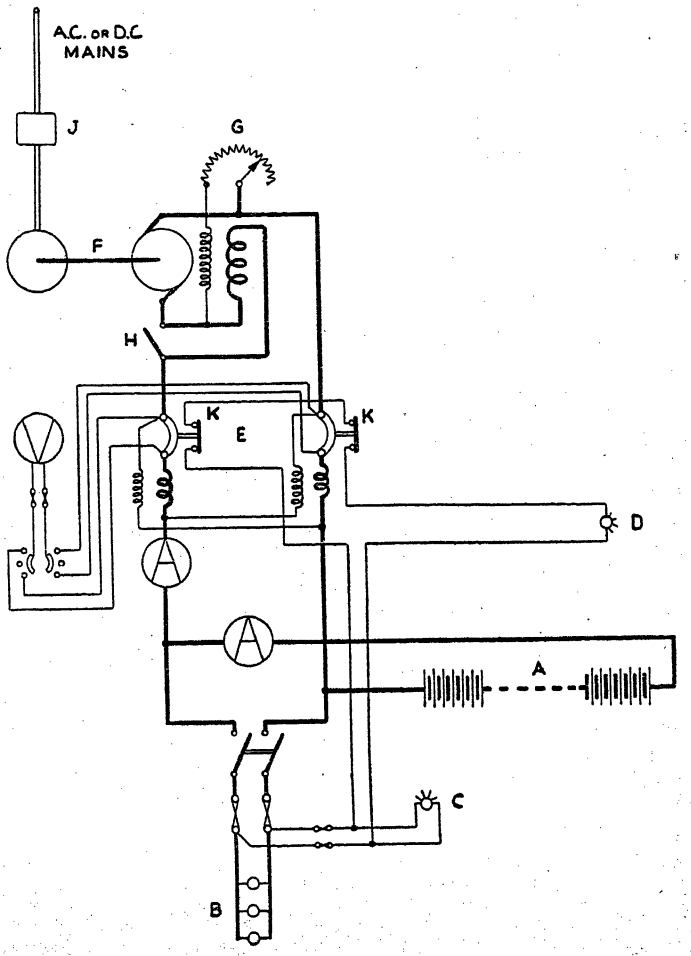


Fig. 1.—Diagram of connections of motor-generator—floating-battery equipment.

A = storage battery
B = safety or secondary lights
C = indicating lamp on panel
D = remote warning lamp
E = reverse-current and overload circuit-breakers
F = motor driving level compound generator
G = shunt field regulator
H = series short-circuiting switch
J = motor starting panel
K = auxiliary contacts which can be arranged for normally on, or normally off, indicating from lamp "D"

The motor-generator set is started up just before the public are admitted to the building and is shut down at the end of the performance. It has, however, the disadvantage that it comes within the running-machinery category, which may cause noise and vibration, while the commutator brushgear and bearings require attention from time to time.

(1.5.2) Valve-Rectifier Equipments.

The development of the hot-cathode full-wave valve rectifier and the improvements over the last few years have provided an alternative to the motor-generator set, and this type of rectifier is now very largely used for small and medium-sized cinema floating-battery schemes. It is cheaper, does not occupy as much floor space, and has the advantages that it is static and reliable and that the life of the bulbs is satisfactory. A typical diagram of a valve-rectifier floating-battery scheme is shown in Fig. 2.

The method of operation is similar to that of the motor-generator set as the lighting load is supplied from the d.c. output of the rectifier, the voltage being adjusted to give a slight charge to the battery. Upon failure of the a.c. supply, the battery supplies the load, and as the valve itself has a non-reverse character-

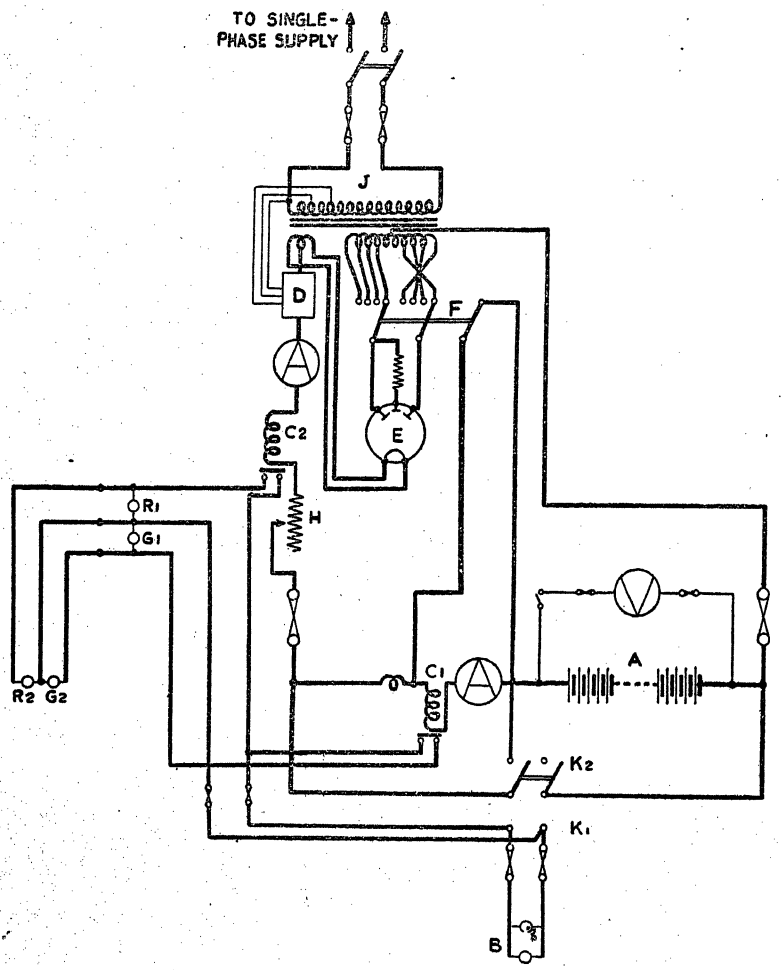


Fig. 2.—Diagram of connections of valve-rectifier—floating-battery scheme.

A = storage battery
B = safety or secondary lights
C1, C2 = relays
D = delay switch to allow filament to heat up
E = full-wave hot-cathode valve
F = regulating switch
H = adjustable resistor control
J = transformer
K1 = lights on
K2 = charging
R1, G1 = red and green signal lamps on panel
R2, G2 = corresponding remote lamps

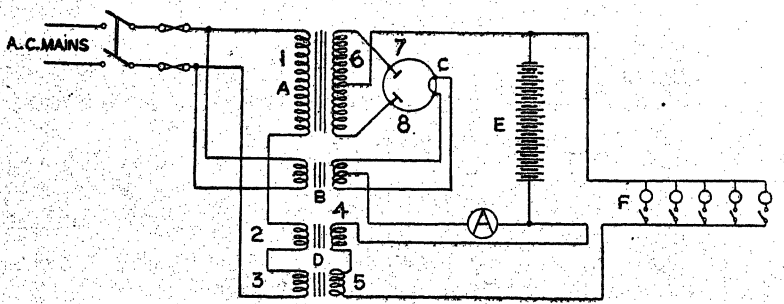


Fig. 3.—Simplified diagram of constant-voltage—floating-battery scheme (British Patent No. 377671).

A = main transformer
B = filament transformer
C = full-wave valve
D = control chokes
E = storage battery
F = cinema safety lights

istic no reverse-current circuit-breaker or other device is required to prevent the flow of current from the battery to the rectifier.

Upon resumption of the a.c. supply, rectification automatically recommences and normal conditions are resumed. The rectifier equipment therefore has an advantage over the motor-generator set in this respect. As, however, the simple rectifier has not the same compounding feature, it is necessary to vary the setting to suit any alteration of the load. An alternative is the mercury-arc rectifier, a number of which have been installed, particularly for larger cinemas and where the battery is of the same voltage as the mains.

(1.5.3) **Metal-Rectifier Equipments.**

The copper-oxide or selenium rectifier can also be used as a further alternative to the motor-generator, and a considerably longer life is said to be obtained from the metal type of rectifier than it is possible to obtain from the valve type. In addition, no heating device is required. Otherwise, the control and layout are very similar to those of the valve type.

(1.5.4) **Constant-Voltage Floating Equipments.**

To overcome the disadvantage of having to alter the setting of the rectifier output to suit changes in the external load, and to ensure that any fluctuation of mains voltage and/or any changes in the external load do not alter the desirable running conditions, various automatic regulating systems have been devised. One scheme achieves the desired result by the use of compensating chokes of special design. A typical example of this is illustrated schematically in Fig. 3. There are two control chokes, the a.c. windings (2) and (3) of which are connected in series with each other and in series with the anode transformer primary winding (1). Any variation in the impedance of windings (2) and (3) causes a similar variation in the voltage applied to the transformer secondary (6), and, in turn, to the valve anodes (7) and (8) to which the secondary is connected. Each choke is fitted with d.c. windings (4) and (5) which are connected in series with each other and with the load circuit.

When the current is small the iron cores of the chokes are only partially saturated. Consequently, the impedance of the a.c. windings is high and the voltage applied to the primary winding is low. When the load current is increased, the choke cores are saturated to a higher degree and the impedance of coils (2) and (3) is reduced, resulting in a higher voltage across the transformer primary and across the valve anodes. By suitably arranging the numbers of turns of the a.c. and d.c. choke windings and the section of laminated-iron core, it is possible to obtain practically constant rectifier output voltage with varying output current.

Although the double-wound chokes do not directly regulate the output voltage to compensate for primary-voltage variations, the desired effect can be achieved by adopting a floating voltage of about 2·15 volts per cell at normal primary voltage. Primary-voltage variations of the order of $\pm 5\%$ have then practically no effect on the current in the battery circuit, owing to the fact that a fully-charged battery has a certain range of voltage in which almost no charge or discharge can take place.

With this rectifier it is unnecessary to provide a time-delay switch. It is desirable, but not essential, to allow a pause between closing the a.c. switch and closing the load switch, to take account of the momentary rush of current, but this is less than with manually-operated rectifiers.

During ordinary recharging after a discharge the automatic

action of the rectifier is cut out, and it is necessary to regulate by the controls provided.

(1.6) Automatic Switching Equipments

The daily-charge-and-discharge battery and the floating-battery schemes were, until quite recently, the only ones acceptable to the Home Office and local authorities for the secondary lighting of cinemas.

On the 2nd September, 1942, the Home Office sent a circular letter to the various Clerks to the licensing authorities under the Cinematograph Act, 1909, stating that the Secretary of State would not wish to raise any objection, subject to certain conditions, to the use of automatic change-over switches in connection with the safety lighting of cinemas during the period of the present war.

The pertinent conditions are, in brief, that the switch shall conform to the appropriate British Standard, that its rated capacity shall be not less than 50% in excess of the maximum safety lighting load, and that a daily recorded test of the switch shall be made before the public is admitted to the premises.

Although, therefore, emergency lighting systems with automatic switching devices can now be used in cinemas, neither they nor the other permissible devices will be described in this Section of the paper as they are dealt with in the later Sections. The equipment described and illustrated by Figs. 5(*a*) and 5(*b*) is suitable for a typical cinema.

(2) HOSPITALS AND NURSING HOMES

(2.1) Hospitals

The particular type of emergency lighting used in a hospital depends on the layout of the buildings and on the amount of lighting required; also on whether the hospital generates its own power and lighting or takes a supply from the local authority. It may be provided in four different ways:—

(*a*) Complete lighting and power services by an alternative supply or an alternative main from the same substation and/or alternative mains from separate substations, or by engine-alternator sets.

(*b*) Partial lighting and power supply by an engine-generator with a battery.

(*c*) Partial lighting by battery only.

(*d*) Partial or local lighting by portable hand-lamps with wet or dry batteries.

In general it has not been considered essential to install equipment to allow for a complete change-over of all the lighting in the hospital, and when a change-over scheme is arranged it is usually confined to the lighting of the operating-theatre block.

(2.1.1) Pilot Lights and Operating Theatres.

In some cases pilot lights have been provided in the wards and corridors in addition to complete emergency lighting in the operating-theatre section of the building. A combination of an automatically switched battery and engine-alternator set probably constitutes the almost ideal equipment for these conditions. The battery is normally of mains voltage and of such a capacity that it can automatically carry the whole of the emergency lighting load for, say, 1 hour. It will, however, rarely be called upon to discharge for this period, as the basis of the scheme is that the engine set shall be started up as soon as the breakdown occurs. This leaves a reasonable standby supply in the event of there being any difficulty in starting up the engine set, although normally a periodical test should ensure that this is in proper order. The alternating current thereby generated takes the place of the normal supply, and the action of the automatic contactor cuts off the battery from further discharge. When the main a.c. supply is resumed the battery is recharged, usually by means of a separate rectifier especially provided for this purpose, and left on trickle charge until the next emergency discharge. A suitable equipment for dealing with a requirement such as this is illustrated by Fig. 4.

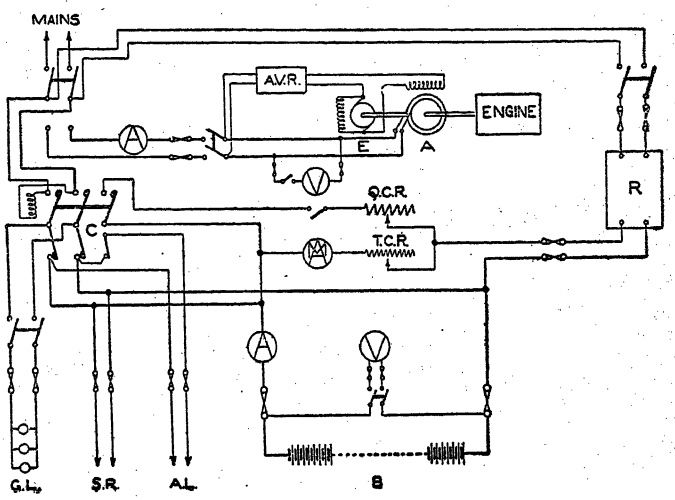


Fig. 4.—Typical automatic switching circuit, incorporating engine-driven alternator.

A = alternator (engine-driven)
A.L. = alarm
A.V.R. = automatic voltage regulator, etc.
B = battery
C = change-over contactor
E = exciter
G.L. = general lighting
Q.C.R. = quick-charge resistor
R = rectifier
S.R. = switch-relay circuit for operating theatres
T.C.R. = trickle-charge resistor

(2.1.2) Total Lighting of Operating Theatres.

When the change-over from the main to the emergency supply for the operating-theatre block is all that has to be dealt with, the more usual equipment [see Figs. 5A and 5B] is a battery that can be put on load automatically in the event of a failure of the main supply. When the load is automatically transferred from the mains, with a barely perceptible flick, to the battery, the surgeons and their helpers are not aware that any interruption has occurred.

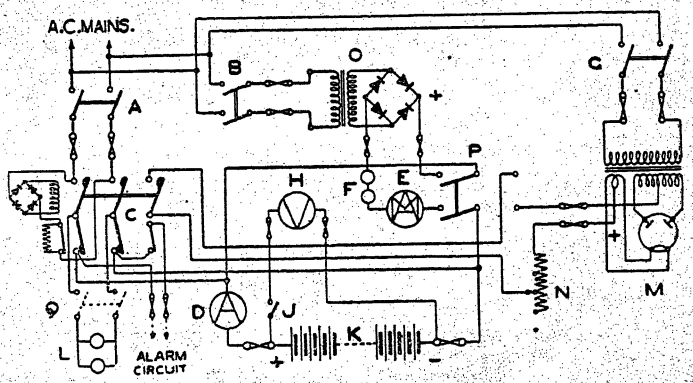


Fig. 5A.—"Maintained" type automatic switching circuit, employing mains-voltage battery.

A = contactor switch
B = trickle-charge rectifier switch
C = change-over contactor
D = ammeter
E = milliammeter
F = lamps for trickle charge
G = quick-charge rectifier switch
H = voltmeter
J = voltmeter switch
K = battery
L = secondary lights
M = quick-charge valve rectifier
N = quick-charge resistor
O = trickle-charge metal rectifier
P = trickle- and quick-charge switch
Q = secondary lighting switch

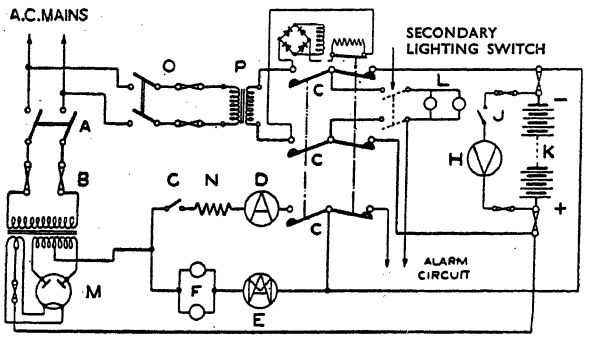


Fig. 5B.—"Maintained" type automatic switching circuit, employing low-voltage battery.

A = rectifier input switch
B = rectifier input fuses
C = change-over contactor
D = ammeter
E = milliammeter
F = lamps for trickle charge
G = quick-charge switch
H = voltmeter
J = voltmeter switch
K = battery
L = secondary lights
M = rectifier
N = quick-charge resistor
O = lighting transformer switch and fuses
P = lighting transformer

(2.1.3) **Period of Discharge of Battery.**

Whilst it is not easy to make any definite ruling to cover every case, it is generally considered that the battery should be of such capacity as will enable it to supply the emergency lighting for such a length of time as would be required at least for performing the operation or for tidying up after the most serious operation, should the supply fail just after this has commenced.

It is now generally considered that 3 hours represents such a period, and this seems to meet most requirements.

(2.1.4) **Partial Emergency Lighting in Operating Theatres.**

There are as yet no regulations governing the installation of emergency lighting in hospitals, and most hospitals are fitted with an equipment which allows only partial lighting of the operating theatre or theatres.

There are, no doubt, reasons for limiting the use of the emergency lighting plant in this respect, but the author feels that the cost of providing a more adequate equipment should not be, as he thinks it is in most cases, the deciding factor. Fig. 6 illustrates the partial emergency lighting of a typical modern operating-theatre block, the normal lights being indicated by the larger circles and the emergency lights by the smaller ones, the operating-theatre lamp being of the shadowless single-bulb type. There is just sufficient emergency lighting in essential positions to enable the operation to be continued or completed by this in the event of failure of the normal supply. Fig. 7 is a diagram of a suitable emergency-lighting equipment.

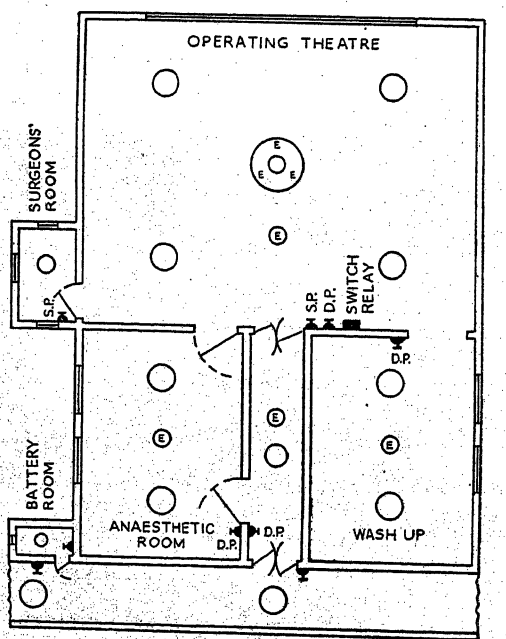


Fig. 6.—A typical modern operating-theatre block.
E = emergency lights. Plain circles represent normal lights.

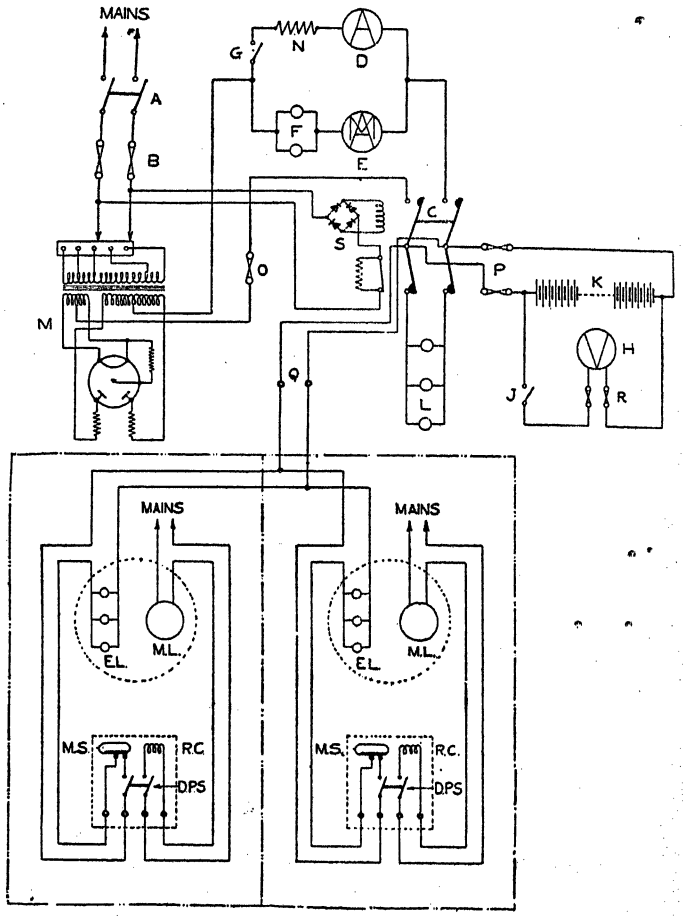


Fig. 7.—Diagram showing use of two combined switch-relays in two operating theatres, in conjunction with one central automatic switching equipment ("non-maintained" type).

A = main switch
B = main fuses
C = change-over contactor
D = ammeter
E = milliammeter
F = lamps for trickle charge
G = quick-charge switch
H = voltmeter
J = voltmeter switch
K = battery
L = general emergency lights
M = rectifier
N = quick-charge resistor
O = rectifier output fuse
P = battery fuses
Q = circuit for switch relays
R = voltmeter fuses
S = contactor coil rectifier
M.L. = main lamp
E.L. = emergency lamps
M.S. = mercury switch
R.C. = relay coil
D.P.S. = double-pole switch

With this arrangement the emergency lights are normally *not* illuminated but are connected to the battery, usually of 25 or 50 volts, by means of the contactor (*c*) when the supply to the controlling coils fails, and they remain so connected until the normal supply to these is resumed. The battery, which is normally maintained in a fully charged condition by means of a continuous trickle charge from the rectifier (M), is then given a charge from the same rectifier by means of switch (G), after which it remains on trickle charge until after the next emergency discharge, and only then, provided the requisite trickle charge has been maintained, does it require a further charge.

Sometimes double-pole switches are used, one pole of which

connects part of the primary circuit and the other pole part of the secondary circuit, to prevent the battery from discharging unnecessarily if a supply failure occurs when the theatre is not in use.

(2.1.5) **Operating-Theatre Lamps.**

The operating-theatre lamp or lamps may be of the cluster or single-bulb shadowless type. The efficiency of the cluster fitting is not seriously diminished by the failure of one or even more of the individual lights, as distinct from the type of shadowless fitting which usually relies on a single bulb to provide the illumination. When the cluster fitting is used the emergency light or lights are usually suspended over or adjacent to it, and no special arrangement of switching the lights is necessary as they are connected to the main contactor. With the single-bulb type of fitting, the emergency lights are usually incorporated in the fitting itself; this is achieved by using a twin-filament bulb or providing three emergency lights within the reflector of the fitting.

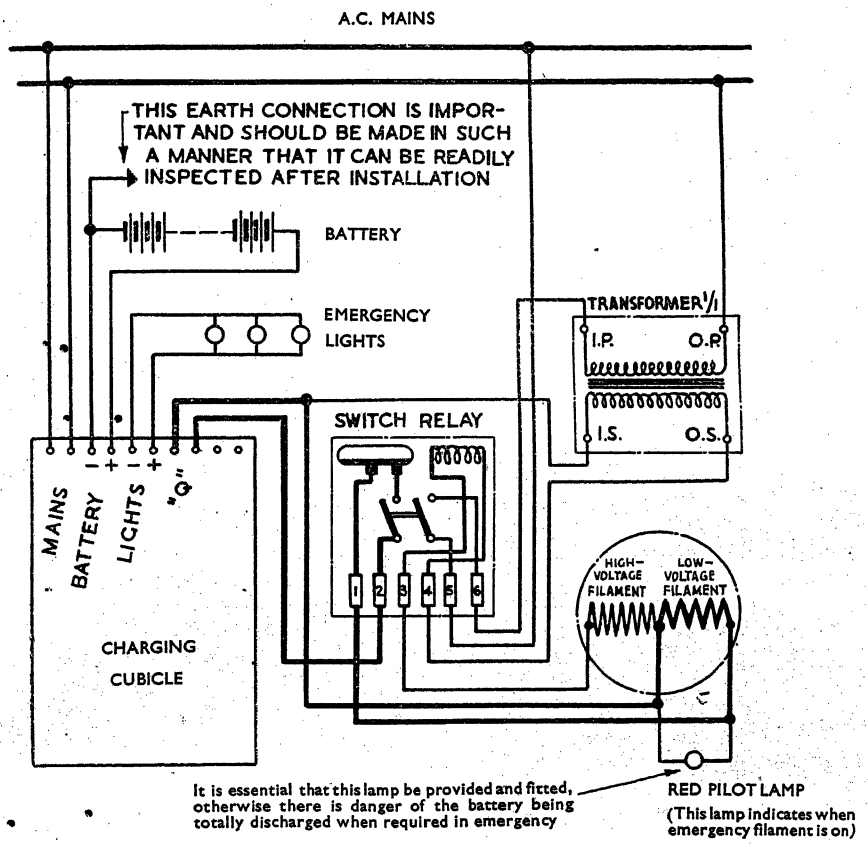


Fig. 8.—Connections for special switch relay.

(2.1.6) **Combined Switch-Relay.**

In all hospital operating theatres utilizing these shadowless fittings, some method has to be provided to bring the emergency lights into action upon failure of the main filament, and this is usually done by employing a combined switch and relay. This is so called because it contains a switch which takes the place of that which would otherwise control the main lamp, and a small mercury switch of relay size which switches the emergency lights into circuit when the current through the series-connected coil fails. The switch-relay is usually of the sunk pattern, with a plated cover, and is fitted into the wall of the operating theatre (see Figs. 6 and 7).

On closing the double-pole switch, the circuit from the battery to the emergency lights remains closed until the coil is sufficiently energized by the current to tip the mercury tube and so open the emergency circuit. The result is that the emergency lights become illuminated momentarily each time the switch is closed, and so give a visual indication that the automatic switch is functioning correctly and that the circuit to the battery is alive.

(2.1.7) **Twin-Filament Lamp.**

With regard to the twin-filament type of main lamp, so far it has been possible to obtain only a 3-terminal arrangement, and although this type of lamp has certain advantages, since the emergency filament is in approximately the same position as the main one, it has obvious disadvantages as compared with the type of lamp in which the main filament is entirely separate from the emergency one, or where separate emergency lights are used.

Fig. 8 illustrates the connections for the switch-relay used to control this type of fitting. The object of the 1:1 transformer is to insulate the system from the mains and allow one pole of the battery to be earthed for safety.

Either type of switch relay would function also on failure of the sub-fuses, the main fuses or the supply.

(2.1.8) **Operating-Theatre Portable Lamp.**

Where it is not considered desirable or economical to install permanent secondary lighting—and this applies more particularly to temporary operating theatres—an entirely separate emergency light is used and is brought into action upon failure of either the main filament or the supply. This is frequently in the form of a trolley which carries the emergency operating lamp and its battery, which can be either of the steel-alkaline or the lead-acid portable type.

Special arrangements have to be made to ensure that the battery is always kept sufficiently charged to perform its function, and also that it is given a recharge after any emergency discharge. The former is achieved, depending on the type of battery used, by regular freshening charges or by having two interchangeable batteries, and the latter by means of a charger also mounted on the trolley, or the battery is taken away to some central charging room where it can receive its recharge.

For these reasons this method is not quite so certain in action or so effective as the permanent installation.

Fig. 9 illustrates an example of this portable lamp which serves a dual purpose, as it is provided with a centre light operated from the mains, and two lights, switched to the battery in an emergency, round the reflector.

(2.1.9) **Hand-Lamps and Torches.**

Hand-lamps and/or torches fitted with either dry or wet batteries of the lead-acid or steel-alkaline type are frequently used to supplement the types of equipment already mentioned, and are sometimes the sole source of emergency lighting. These should be kept in well-defined and convenient locations and

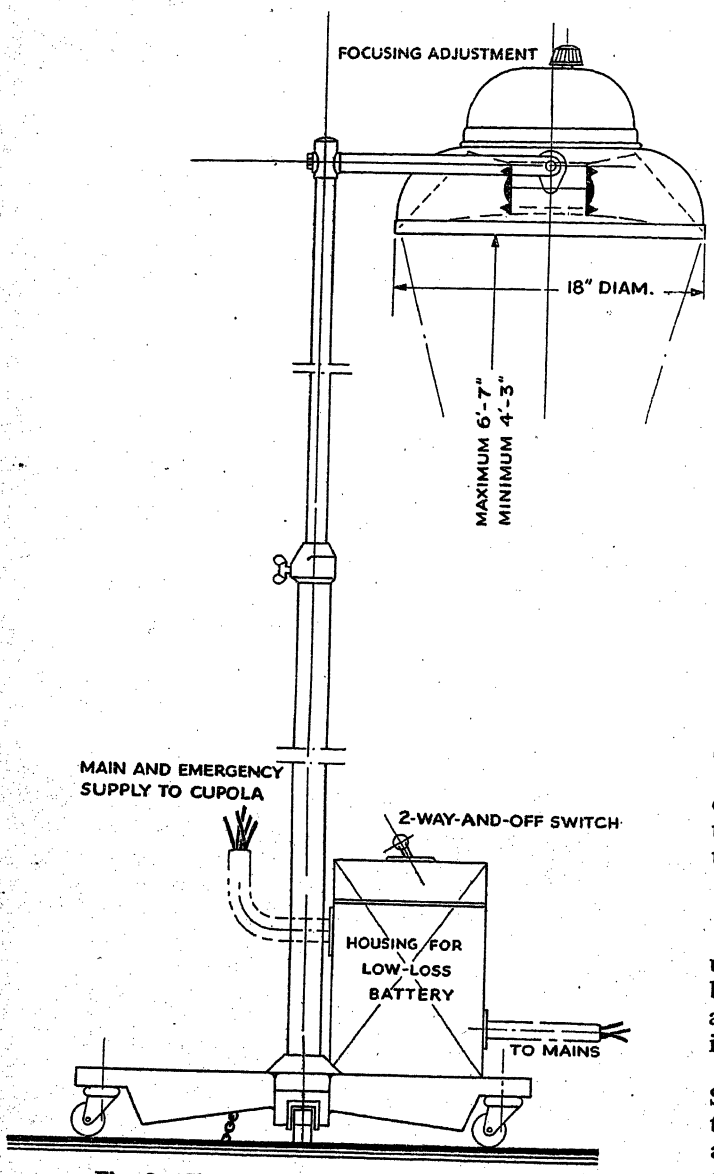


Fig. 9.—Shadowless portable operating-theatre light.

therefore readily accessible to those members of the staff who may require to use them and who should, of course, be well aware of their location.

Whichever type of portable battery is used, it is most important that some regular routine systems of (*a*) inspection of dry batteries, and (*b*) charging of wet batteries, should be instituted, as otherwise the lamps, not being in regular use, will usually prove ineffective when the emergency arises.

(2.2) Nursing Homes

Following the passing of the Nursing Homes Registration Act, 1927, it became compulsory for all premises being used, or which were intended to be used, as nursing homes to be registered as such and to be subject to inspection by the appropriate local authority. Most local authorities have a schedule of requirements which has to be met before the premises concerned can be registered and the home opened. One of the requirements, if an operating theatre and/or labour ward are to be included, as is usually the case, is the provision and installation of an approved emergency-lighting equipment.

The various types of equipment described in Section 2.1 are suitable for the larger nursing homes, but generally they need not be of an elaborate nature, as the operating theatre and labour ward in a nursing home are very often small compared with those in hospitals, and the number of emergency lights required is correspondingly less.

In the operating theatre, therefore, they are usually limited to the number necessary to provide light over the operating table, and where the single-bulb, shadowless type of lamp is used a 12- or 24-volt battery of sufficient capacity to illuminate the 3 lights round the reflector for a period of 3 hours with the necessary two-rate charger and switch-relay is a generally approved circuit.

In order to provide means for a more comprehensive test of the emergency lights than that provided by the switching-on of the main lamp as already described, and to avoid having temporarily to withdraw local fuses or cut off the main a.c. supply, some authorities require a normally-closed push-button test switch to be included in the a.c. circuit to the main lamp. If a cluster fitting is used as the operating-theatre light, then the switch-relay is usually omitted and a single-pole contactor connects the emergency lights to the battery upon failure of the supply. If the labour room or rooms as well as a shadowless fitting in the operating theatre have to be dealt with, then the equipment shown in Fig. 7 is suitable.

The portable type of lamp with main and emergency lights and other supplementary means of emergency lighting described in Section 2.1 are also frequently used.

Some authorities also make the inspection agreement scheme described earlier in the paper one of the conditions to be observed to achieve registration—a feature particularly recommended for this class of installation.

(3) PUBLIC BUILDINGS, ETC.

As yet there are no regulations governing and compelling the use of an emergency lighting equipment in town halls, large blocks of offices, restaurants and similar places, except in so far as may be necessary to cover that part of the building for which it is desired to obtain or retain a music and dancing licence.

In such places equipment such as has been described in Section 1 would be suitable. In addition, certain local authorities have approved the use of the automatic switching systems already described in Section 2.1 (one authority requires duplicate switches illustrated in Fig. 10). Such systems enable the battery to be trickle-charged continuously, and this feature is particularly useful in the type of building covered by this Section as the licensed parts of the premises are rarely used regularly throughout the year, and thus differ from nearly all cinemas and theatres.

(3.1) Town Halls with Cinema or Concert Hall

Apart, however, from anything required to meet music and dancing regulations, in many modern buildings it has been considered desirable to provide some form of emergency-lighting equipment which, coming into action in the event of a failure of the usual source of light, enables work to be carried on for a period and, particularly, allows the occupants to regain the street with the minimum of inconvenience. Where both requirements have to be met, either two separate equipments, each dealing with its own part of the building, or one equipment to deal with the whole building, can be used. Each scheme has its advantages. In the former the specification for the panel and the capacity of the battery for the music and dancing section of the building can be such as to conform to the local regulations, while the equipment for the emergency lighting of the remaining portion of the building can then be that which best fulfils the

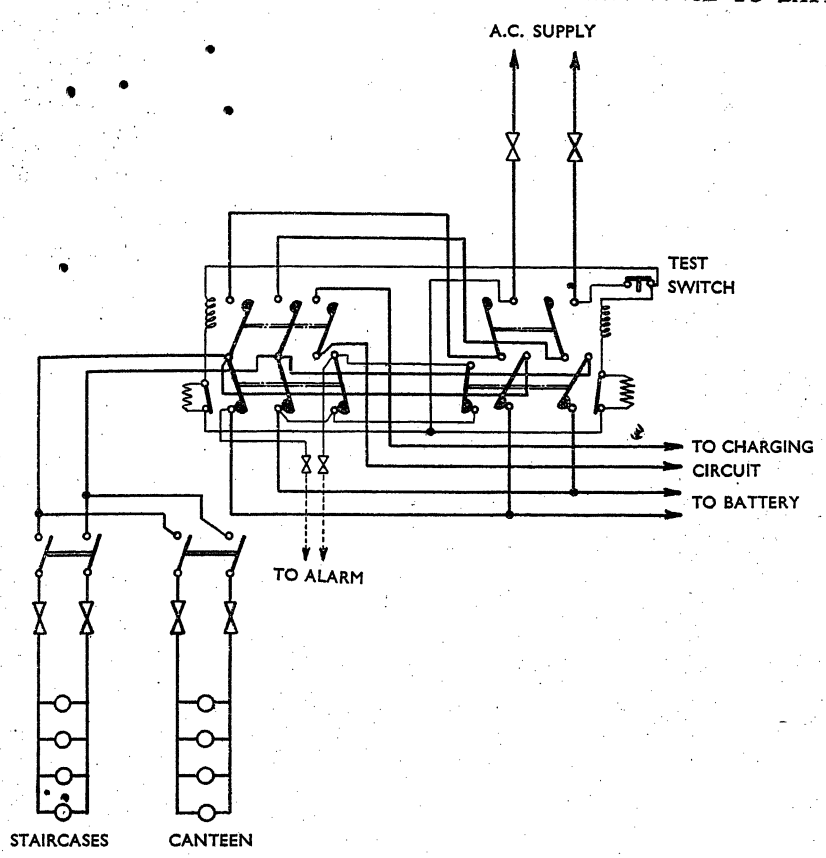


Fig. 10.—Duplicate contactors.

conditions to be dealt with, each equipment being located in the most suitable position.

If, however, one equipment is to be employed to deal with the whole building, then this, since it has to comply with the local regulations, may not necessarily be the most suitable one, and some difficulty may arise on the question of the battery capacity, as it is necessary to limit any discharge which may be required to deal with the emergency lights in that part of the building not licensed, to ensure that sufficient capacity remains to cover the lights in the music and dancing section.

Fig. 11 represents a typical diagram where one equipment and one battery are used, while two automatic switching systems or a floating scheme and one automatic switching system are used for the two-equipment arrangement. Most authorities insist on the two-equipment arrangement, but some allow the one-equipment scheme with the necessary safeguards.

(3.2) Offices and Flats

In the larger types of building (blocks of offices or flats) the emergency lighting can be brought into operation by hand or by automatic means, and can be supplied by a maintained or a non-maintained type of circuit. "Maintained" is the conventional description of the type of circuit used when it is desired that the emergency lights shall form part of the normal lighting and be switched on or off with the remainder of the lights. The "non-maintained" type is used when the emergency lights are required to be illuminated only upon failure of the normal supply and are therefore additional to the ordinary lighting.

Both types of equipment require circuits for the emergency lights entirely separate from those supplying the normal lighting, and these circuits are connected to the secondary lighting fuse-boards which, in turn, are connected to the secondary lighting control panel. Where the emergency lighting is of the "maintained" type and is spread over a number of floors, each of which is wired on a separate phase of a 3-phase supply, it is usual to employ a scheme which allows for the emergency lights on any particular floor to be supplied from the phase which supplies the normal lighting of that floor. Fig. 12 shows diagrammatically an interesting example. The maintained secondary or emergency lighting is distributed to the various floors through two 3-phase 4-wire risers which are, of course, separate from the risers supplying the general lighting. These emergency risers normally carry a 3-phase supply, via their change-over contactors, to the secondary lights which, under these conditions, merely form part of the general lighting. Should the a.c. supply through either contactor fail, however, the contactor changes over and the 3 phase wires are paralleled together and connected to the battery positive, whilst the neutral wire becomes the negative. Obviously, under these conditions, the neutral wire and its corresponding contact on the contactor have to carry the sum of the currents in the phase wires and must be of three times the cross-section (this is indicated by thickening in the diagram). In addition they must be carried right through to the fuse-boards where the splitting into 2-wire circuits occurs.

The contactors are so constructed that all the phase arms operate as one unit, and as the lighting circuits connected to each are entirely separate no short-circuiting of the phase-wire should occur if the contactor fails to operate correctly.

In an office building or block of flats, where the corridors and staircases only are to be wired for emergency lighting, the maintained type of equipment, indicated in Figs. 5(*a*) and 5(*b*), is suitable. The circuit is normally supplied from one phase or, if that fails, from the battery, and there is no need to allow for the separate failure of the other two phases. In other cases where 3-phase protection is required, two potential relays are included, the coils of these being energized by separate phases from that energizing the contactor coil, and the supply to this being in series with the two relay contacts. If, therefore, a phase and/or fuse failure (depending on the point to which the particular relay is connected) occurs, the supply to the contactor coil is broken and the battery brought into action.

The arrangement has the possible disadvantage that all the emergency lighting is brought into operation, whereas it is possible to use three separate change-over contactors when only the emergency lights in that part of the building affected by the failure are supplied by the battery.

(3.3) Large Stores

The equipment most suitable for large stores and retail establishments depends on whether (*a*) it is desired that business should be carried on during the breakdown, in which case the degree of illumination provided under emergency conditions must be such as to allow for this, or (*b*) it is merely desired that sufficient lighting should be provided to prevent panic and theft and to enable the customers to leave the building.

(3.4) Complete Emergency Lighting

To meet the conditions under (*a*) above, the ideal equipment is the combination of the automatically-switched battery and engine-generator set or sets described in Section 2.1. The immediate supply from the battery would prevent any complete

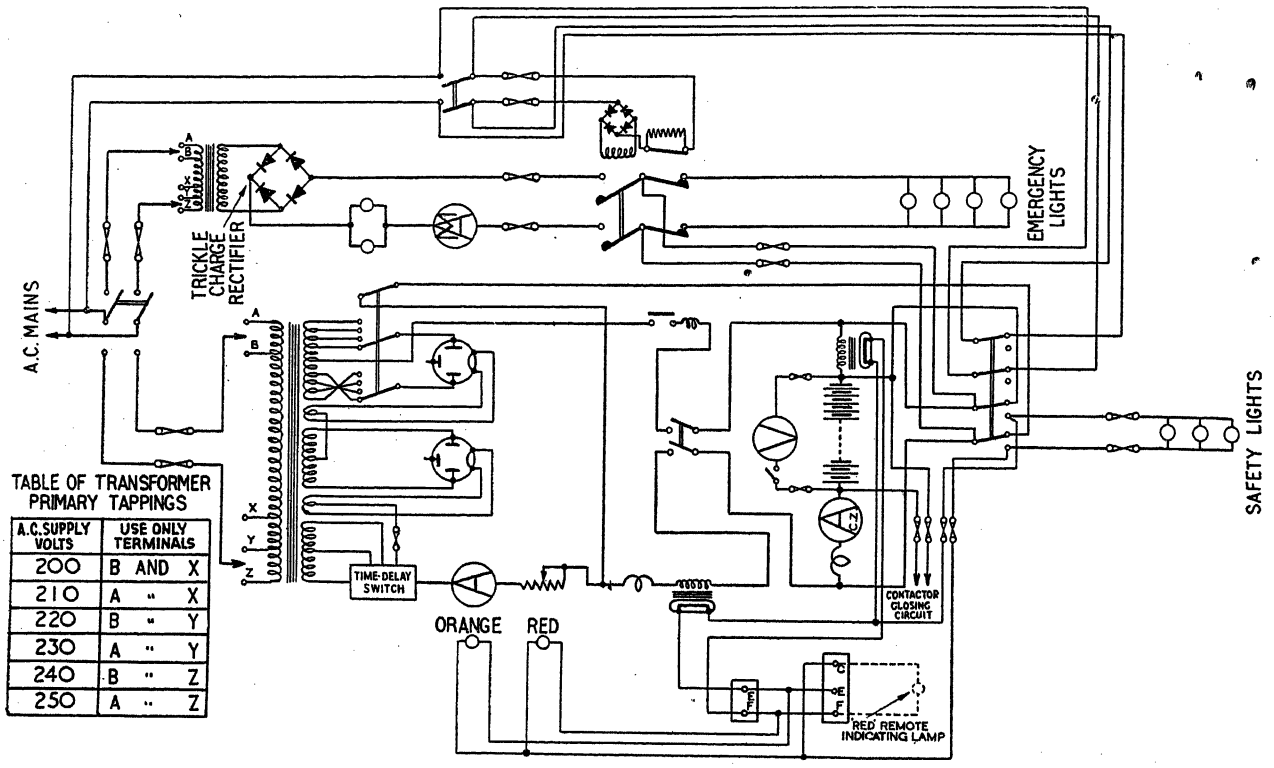


Fig. 11.—Combined floating and automatic switching equipment.

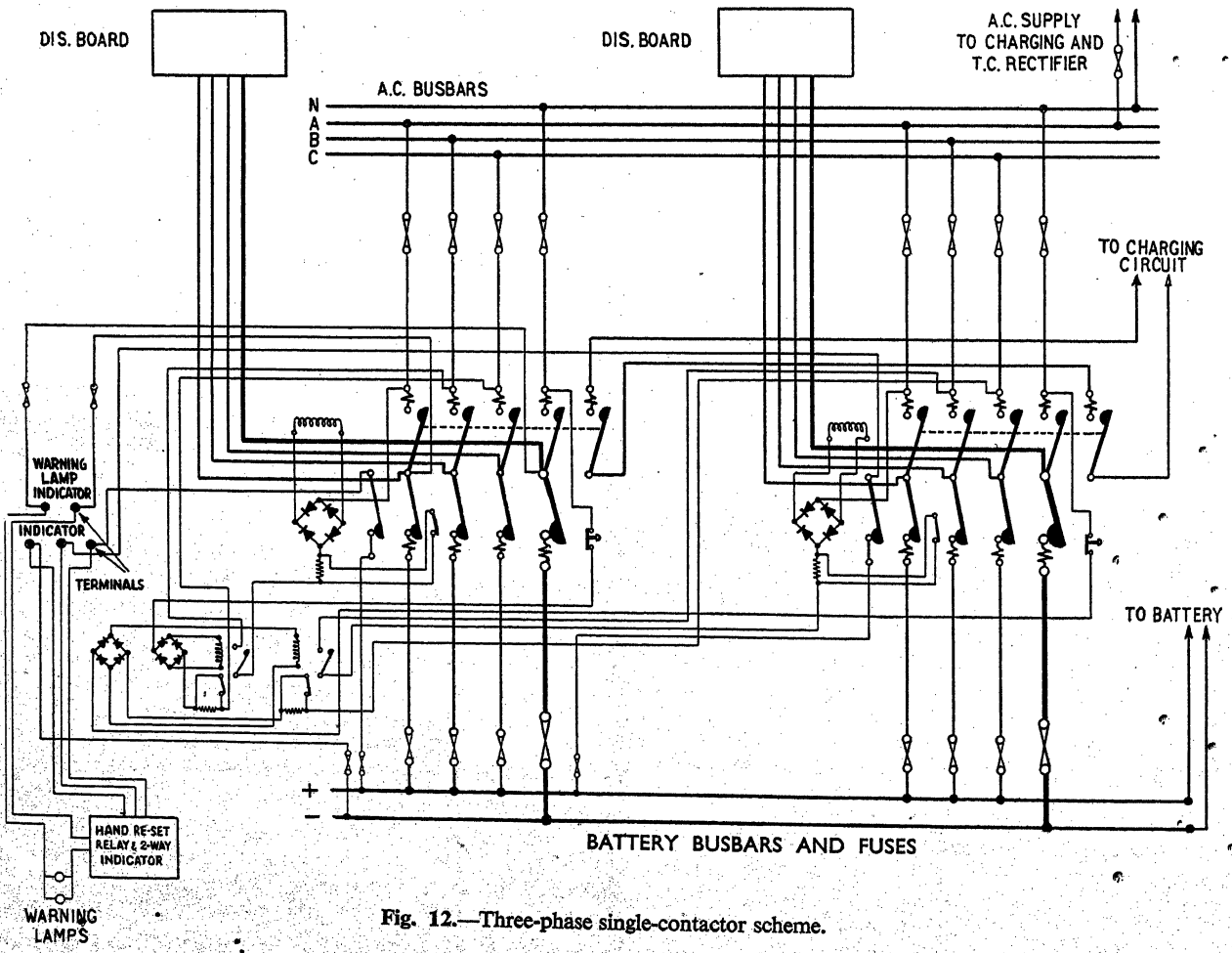


Fig. 12.—Three-phase single-contactor scheme.

blackout, whilst the capacity of the engine sets would be sufficient to provide ample light to carry on the merchandizing until such time as the ordinary supply was resumed. With this combination it can be arranged that the battery shall deal with all the emergency lights, or, by a suitable arrangement of the circuits, only an essential proportion of them. Even if it is desired that the battery shall cater for all the emergency lights, it need be only of sufficient capacity to supply these for, at the most, half an hour, while if it has to deal only with a proportion of these lights a correspondingly smaller battery can be used. It might here be stated that a 230-volt lead-acid battery of 60 Ah capacity will give a discharge of 10 kW for practically half an hour—equivalent to a considerable amount of light for emergency conditions—and as a battery of this voltage and capacity can be accommodated on a 3-tier stand in a room measuring 10 ft × 5 ft the combined equipment need not be much more expensive or require much more space than the simple engine-generator set.

If, however, it is not considered essential to have complete continuity of light, the engine-generator set or sets without the battery would probably prove to be the next best method of providing the emergency supply, always assuming that it is not possible to obtain this from a public supply entirely separate from that of the normal lighting. These sets can be of the automatic remote-control type where the circumstances justify it, or of the more usual manually-operated type, started up by battery or compressed air.

The fuel used, again, is very largely determined by the relative factors of the particular case under consideration, and can be either diesel oil, petrol or paraffin.

The storage of the fuel selected, compliance with the local authority's regulations on this point, the adequate disposal of the exhaust, the method of cooling to be adopted, and the elimination of vibration, are all problems calling for solution when the engine-generator set is employed. As, however, these problems are not peculiar to emergency lighting systems, and apply generally wherever engine-generator sets are used, they do not come within the scope of this paper.

Where the load justifies it, and where it is desired to limit the risk of a complete breakdown of the emergency plant during an interruption of the supply, two separate sets can be used instead of one.

(3.5) Partial Emergency Lighting

The author has not been able to obtain details of any of the large stores employing this combination of battery and engine-generator set or the engine set alone, solely for emergency lighting purposes. The more usual scheme, of which there are a number of cases, is the automatically-operated battery equipment to provide for the conditions under (*b*) (Section 3.3). This supplies an emergency lighting circuit or circuits throughout the building, the emergency lights being sufficiently numerous and of adequate wattage to enable the public to remain in the building in reasonable comfort until the supply is restored, or to leave the building without danger to themselves or to others. It also enables the sales staff to keep under continuous observation the goods on display.

In view of the large number of people (mostly women and children) who crowd the floors and particularly the basements of the large stores at sale times and Christmas, the author is of the opinion that the regulations of the local authorities should be extended to cover buildings of this nature and thereby ensure that adequate emergency lighting is provided.

(4) FACTORIES

The problem of the emergency lighting of factories is, as in the other types of buildings already dealt with, very largely one of making a decision as to the purpose for which the emergency lighting is required.

Before it became necessary to make provision of this nature to meet A.R.P. conditions, it was generally considered that it would be sufficient to provide enough lighting in a factory to enable the work people to remain in the building until the main supply was resumed, or to leave it without danger to themselves if it was decided that the breakdown was of such a nature that it was useless for them to remain.

Where little or no machinery is employed for the functioning of the factory, it is possible to continue work under emergency conditions by the provision of an engine-generator set or sets and/or a battery, but, as is more frequent, when the power goes off the work has to cease, and it is therefore unnecessary and uneconomical to provide more than pilot lighting for emergency conditions.

Any of the equipments described in the earlier parts of the paper are therefore suitable for dealing with these conditions, and if the battery is of sufficient capacity to provide light for 3 hours at the most, sufficient reserve should be available to cover all requirements.

Here, again, it might be considered that an adequate system of emergency lighting, especially in certain types of factories, is essential, and that the Factory Regulations should be amended accordingly.

(5) A.R.P. SERVICES

(5.1) General

Before and during the early part of the war, it was thought that gas would be one of the major offensive weapons to be guarded against, and all rooms and areas selected for use as shelters had to be made gas-proof.

This point is stressed because it had a very definite bearing on the type of emergency lighting equipment which could suitably be used in these shelters. Any form of lighting which consumed oxygen, such as gas, candles and oil lamps, added to the problem of ventilation if this were provided, or, if the room were completely sealed, as some of the smaller shelters were, it limited the time of comfortable occupation. Although, therefore, a large number of hurricane lamps were purchased for use as emergency lights (and in some cases they were intended to be the sole means of lighting in public underground shelters, as it was not always possible or desirable to connect these to the public supply), electric lighting in the form of dry- or wet-battery torches, hand-lamps, accumulators of the steel-alkaline type and lead-acid type with suitable chargers, and engine-generator sets for hand or automatic starting, proved to be the most suitable method of providing the service. When hurricane lamps are used, arrangements have to be made to ensure that they are kept clean, trimmed and supplied with oil. If they are retained permanently in a particular shelter, it is advisable that they should be placed after use in a cupboard which can be locked, the key being in the charge of the shelter warden. Equipment had to be obtained and stored until war broke out, and it became quite a problem where batteries were to be used to decide how they could be stored indefinitely without depreciation and with the minimum amount of trouble in maintenance, and yet be available for practically immediate use when required.

(5.2) Steel-Alkaline Battery Equipment

These conditions were suitable for the steel-alkaline type of battery, and a large number of these were ordered for use with hand-lamps. Self-contained, transportable equipments were obtained to provide for those shelters where lighting of a more permanent nature than could be provided by hand-lamps was required.

The battery was usually either of the 6- or 12-volt type with a

capacity of 25–40 Ah, to supply the desired emergency lighting for 6 hours.

It was intended that this unit, with the three emergency lights wired to suit the shelter concerned, should be stored away until war broke out, when it could be installed in the shelter and connected to the mains by means of the cable attachment provided. While in store, the battery would normally require only an annual freshening charge to keep it in condition.

(5.3) Dry-Battery Torches

In some places dry-battery torches and hand-lamps were obtained, but as these deteriorate whether or not they are used and have a definite shelf life, their use became somewhat of a risk owing to the danger, once war broke out, of renewals being unobtainable.

(5.4) Dry-Charged Lead-Acid Batteries

At least one of the manufacturers of lead-acid batteries produced a "dry-charged" type of cell for use with transportable units to meet the particular conditions. These cells, being sealed, can be stored away, each with its bottle of electrolyte, until they are required to be put into service, when the seal is broken and the electrolyte poured into the cell. They are then ready to give an immediate discharge, if necessary, the capacity available being inversely proportional to the period of time they have been in store. If, however, time is available (and in most cases it is), it is desirable to give the cells a short charge to bring them to a fully charged condition. They then function as a normal lead-acid battery.

It was considered that the 6- and 12-volt batteries used in the popular makes of motor-car, being portable and easily obtainable in all parts of the country, would be the most generally suitable type of battery for A.R.P. emergency lighting services.

Batteries of this type were therefore made available in a dry, charged state, so that they could be bought and stored, with the advantage that if after they were put into service renewals or additional batteries were required, these would be obtainable.

(5.5) British Standards Institution A.R.P. Specifications

The British Standards Institution issued a series of specifications at the request of the A.R.P. Department of the Ministry of Home Security, dealing with the equipment recommended for the lighting of various types of shelter. These are BS/A.R.P.3, 6, 7 and 26. They will be found to cover almost every type of shelter, and complete equipments were made up by various manufacturers to comply with them. A number of these equipments are in use. A considerably larger number of the more comprehensive automatic switching equipments already described in the paper have been installed for A.R.P. services in the larger factories and buildings. In the majority of cases, however, especially in public shelters, the emergency lighting equipment consists either of hurricane lamps or of a number of 6- or 12-volt car-type batteries fitted with wing-nut terminals and a convenient charger, and these are operated according to the procedure laid down in Part 1 of BS/A.R.P.6.

(6) ACKNOWLEDGMENTS

The author wishes to thank all those who have helped him in the preparation of this paper, including his colleagues of the Chloride Electrical Storage Company's staff, officials of the London County Council, and Britannia Batteries, Ltd. He would also like to express his thanks to Technical Lights and Equipment, Ltd., and to the Chloride Electrical Storage Co., Ltd., for permission to publish the illustrations, some of which have already appeared in the *Journal*.

A number of the circuits incorporated in the paper are protected under British Patent No. 313248.

(7) REFERENCES

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Statutory Rules and Orders, 1923, No. 983. Regulations, dated July 30th, 1923, made by the Secretary of State, Home Office, under the Cinematograph Act, 1909.

E. C. McKINNON: *Journal I.E.E.*, 1928, **66**, p. 453; and 1940, **87**, p. 225.

(8) APPENDIX. BATTERIES

As the efficacy of most of the equipments described in this paper depends on the full capacity of the battery being available to meet the emergency whenever it arises, and as the cost of renewals and maintenance of the battery has an important bearing on the type of equipment to be installed, it will be appropriate to devote some space to this part of the equipment.

(8.1) Lead-Acid Batteries, Planté Type

For some years past it has been an established practice to maintain certain types of lead-acid batteries installed for emergency purposes in a fully-charged condition by means of a continuous trickle charge, the amount of current required being that necessary to neutralize or compensate for the losses which would occur if the battery were on open-circuit.

(8.2) Correct Trickle-Charge Rate

The correct trickle-charge rate, which can be calculated fairly closely, is that which maintains the specific gravity of the electrolyte at the fully-charged figure without producing gassing. If a fall in gravity occurs over a period, the rate should be increased, while if gassing occurs the rate is too high and should be reduced. After the alteration in the rate has been made, observation should be maintained over the next few weeks to ensure that the desired result has been obtained. It is important to note that some little time must elapse before the change in the trickle rate can show effect.

It is quite easy to obtain and maintain the correct rate of charge, and, provided a suitable type of battery is continuously trickle-charged at the correct rate, the full capacity will always be available when required; it is neither necessary nor desirable to give it cycles of discharge and charge to achieve this result. The battery does, of course, require a recharge after an emergency discharge, and it is important to establish a routine to ensure that the recharge is given reasonably quickly after the emergency discharge so as to bring the battery to a fully-charged condition to meet any further discharge which may be required. The open-circuit trickle-charge, by itself, is not sufficient to recharge the battery.

(8.3) Automatic Recharging

There is no great difficulty in providing automatic means for giving the higher rate of charge after any emergency discharge of the battery. A suitable potential relay or set of relays can be arranged to control the commencement and finish of such an automatic charge, and there are examples in service. One possible drawback is that the equipment may be looked upon as so self-sufficient that the battery may be neglected, with the result that the very infrequent but necessary topping-up is overlooked.

(8.4) Life of Plates

It may here be noted that it has not yet been possible to determine the life which can be obtained from the plates of a battery correctly worked under this system, as those batteries installed from 1927 onwards are in excellent condition and, so far as can be ascertained, will continue to give first-rate service for many more years.

The type of lead-acid battery which is suitable for trickle charging is that fitted with Planté positive plates and box- or cage-type negative plates.

(8.5) Lead-Acid Pasted-Plate Types

Batteries fitted with plates of the pasted type and with antimonial lead grids do not appear to be suitable for working under these conditions, and as the standard batteries used on motor-cars and wireless sets are constructed with plates of this nature a different procedure has to be adopted when cells of this type are used for emergency purposes to ensure that they are in a suitable condition to give the emergency discharge. The procedure recommended for this cell consists in giving freshening charges at regular intervals, and whilst the rate and duration of these charges and the period which would elapse between them varies according to the age, condition and type of cell, it can be generally stated that the charges should take place at least once a month and be continued until the specific gravities have remained constant for 2 hours at a charge rate not less than approximately half the normal rate. The recharge should be given as soon as possible after any emergency discharge.

(8.6) Distilled Water

When a battery is regularly discharged and charged, an appreciable amount of distilled water is required to maintain the correct level of the electrolyte, mainly owing to the gassing which occurs towards the end of each recharge. With lead-acid batteries worked on the trickle-charge system, little water is necessary as the occasional recharge after an emergency discharge need be continued only until the gassing point is reached, when the loss of water is negligible. Some loss of water due to draught and evaporation occurs if open-type cells are used, but as the sealed-in type of cell is now very largely superseding the open type, and as the majority of emergency lighting equipments require a battery of a capacity within the sealed-in range, the loss due to this cause is almost negligible.

(8.7) Steel-Alkaline Batteries

There are two distinct type of steel-alkaline batteries, namely the nickel-iron and the nickel-cadmium, and the latter is more generally used for emergency lighting equipments in this country than the former. These cells are not usually trickle-charged as the open-circuit losses are very small, and it is customary to give charges at intervals to ensure that the full capacity is available to deal with an emergency discharge.

The specific gravity of the electrolyte does not alter appreciably on charge or discharge, and it is therefore not possible to ascertain the actual state of charge of any steel battery by hydrometer readings. This can be done by adjusting the current to the normal rate for a few minutes, obtaining the voltage reading and comparing this with that shown on the standard curve of charge and discharge for the battery concerned. Evaporation should be made good by the addition of distilled water, and it is important to ensure that the level of the electrolyte does not fall below the tops of the plates.

It is advisable to renew the electrolyte at intervals, the frequency of the renewal depending on the service conditions.

If it is desired to trickle-charge the nickel-cadmium cells, it is usual to arrange for a rate of 1 mA per ampere-hour capacity of the battery.

The boxes used for alkaline batteries are normally of steel with welded seams, forming a strong type of container, but batteries of this type can be obtained in glass jars if desired.

(8.8) Stands

Stationary cells of both types are usually arranged on wood stands in a manner to suit the space available for the accommodation of the battery. When a lead-acid battery is employed, the sealed-in type of cell in robust glass container is usually selected if the capacity required comes within the range. The advantage of this type of cell, in addition to its heavy Planté positive plates and box negative plates, is that their condition can readily be seen through the moulded glass. Another feature is the ebonite or moulded-composition lid which prevents the entry of dust and dirt into the electrolyte, and, conversely, the "creeping" of the electrolyte: this minimizes the effect of the gassing when the cells are on charge and thereby allows the battery to remain dry.

The cells should be so placed on the stand that at least one side of each is readily visible, and at such a height that topping-up with distilled water can be easily carried out and the hydrometer readings conveniently taken.

The steel-alkaline batteries are usually housed in wooden crates, and the purpose of the stand is merely to allow them to be placed at a convenient height for topping-up and cleaning and for insulating the cells from the floor of the battery room.

(8.9) Inter-Row Connections

The individual-cell connectors are usually provided as part of the cell, but the inter-row connectors should preferably be of copper rod of suitable diameter to carry the current, particularly when open-type cells are used. Vulcanized-rubber cable can, however, be used, particularly with the sealed-in type of cell, if the insulation is cut well back from the cell terminals.

(8.10) Battery Room

The battery room should, if possible, be in such a position that the cells can be inspected by daylight, but it is frequently impossible to arrange this, and in any event adequate artificial lighting should be provided to enable the inspection and maintenance of the battery to be effectively carried out. A secondary lighting point should always be allowed for in the battery room.

It is not necessary to take any special precautions with regard to the finish of the walls and floor of the battery room for either type, as under proper floating or trickle-charge conditions no gas is evolved. A certain amount of gas can, however, be given off towards the completion of the recharge after any emergency discharge or after the regular monthly recharge in the case of floating batteries, and ventilation should therefore be provided.

(8.11) Voltage Characteristics

The average discharge voltage of a lead-acid battery at the 3-hour rate being 1·89 volts per cell, and the corresponding figure for the nickel-cadmium type being 1·135 volts per cell, the numbers of cells of the two types used to give any required voltage are in the above proportion—the conventional number for a nominal 100-volt supply is 50 lead-acid cells and 84–85 nickel-cadmium cells. It is usual to arrange for a half-normal charge rate to a final voltage of 2·75 volts per cell for the lead-acid type, while the nickel-cadmium type is usually charged at the normal rate to 1·8 volts per cell.

(8.12) Floating Batteries

Batteries operating under floating conditions are not quite so easy to maintain as those working under the open-circuit trickle-charge scheme, unless the constant-voltage equipment is used.

Care should be taken that the setting of the rectifier is correct, and the specific gravity of the pilot-cell electrolyte in lead-acid batteries, and the voltage in the steel-alkaline type, should be read not less than once a week to ensure that the battery is receiving a charge and is not discharging. Some authorities also make the requirement that these batteries should supply the emergency lights for the last three hours of the performance not less than once a month so as to ensure that the required capacity is available. The recharge has to be given on the morning of the following day before the public are admitted to the building.

DISCUSSION BEFORE THE INSTALLATIONS SECTION, 11TH NOVEMBER, 1943

Mr. F. C. Raphael: How does the author manage so easily to convince his clients and the authorities that they should sanction a standby or emergency equipment, except where it has to be provided in order to conform with statutory obligations? I find Government Departments, in particular, extremely reluctant to grant subsidies or even permits for this purpose. Even in hospitals, in 1939, I was usually requested to confine my activities to the operating theatre.

I should like the author to throw some light on the following passage from the code of one of the county councils: "Except in the case of Cinematograph Theatres and Premises licensed for Stage Play performances, an approved automatic equipment designed to throw the safety lighting on to the battery (3-hr capacity) in the case of a failure of the primary supply will be permitted, provided that the operating mechanism is in duplicate." Do those last words merely imply a reverse-current breaker on each pole, or does the author think something more is wanted in the way of duplicate apparatus?

Particularly for cinemas it is generally agreed that the motor-generator is out of date; it is being very efficiently replaced by the valve rectifier with choke control. I think that is the author's view. What does he consider to be the best voltage for the safety circuit in a cinema?

In hospitals the low-voltage supply is sufficient for the operating theatre, but I have always considered the double-filament lamp to be bad practice; it does not give full emergency protection, for if the lamp breaks or the second filament burns out with the first, there is no emergency lighting whatever.

When first installing the so-called "Keepalite" equipments, I took exception to the bulky switch on the wall of an operating theatre—I think the size has since been slightly reduced—and I insisted on the circuit being altered so that the relay could be placed on the battery control-board. At that time the combination was not sparkless. I do not like the two-way switch shown at the top of the portable set in Fig. 9; two coupled sparkless switches should replace it.

I was very interested in the author's large 3-phase lighting installations, but one is apprehensive about installing an automatic switch for switching off and then short-circuiting the three phase-wires. The time-lag between these two operations may depend on the setting of the switch arms, which might fail at any time. Has the author many of these equipments in use? In one hospital with which I have had to deal, the installation was 3-phase, very large and distributed, and the L.C.C. offered to have one of their small mobile 230-volt Diesel sets available if difficulties arose. The capacity of this set was but a fraction of the full load of the hospital and an appropriate loading had to be chosen for it. This meant picking out on the main switchboard a number of circuits and sub-circuits for the emergency load, and installing three simple hand-operated throw-over switches for connecting to the temporary supply when necessary, with such arrangements as to make the equipment virtually foolproof.

In Section 4, dealing with compulsory emergency lighting under the Factories Act, the author's suggestions seem very drastic. In some factories provision has been made voluntarily, but in that case the pilot lamps and exit lamps would be connected to the batteries serving the A.R.P. shelters. I have known one or two instances of that, but we ought not to ask for emergency lighting to be compulsory in every shop or in certain shops; it should be left to the discretion of the occupier. It was recently suggested that separate safety lighting should be installed on staircases and in corridors of schools. Hitherto, it has been considered sufficient to provide gas jets for the safety-exit lighting of school halls, but the more frequent use of a cinematograph projector in such halls may ultimately make a low-voltage battery standby desirable.

Mr. T. C. Elliott: I strongly endorse the author's recommendation of periodical inspections, having come across some very bad cases of neglect or ignorance. Nevertheless, this type of equipment does fulfil its purpose quite well, and it is indispensable in places of public amusement and hospitals. In a large hospital in the West End of London automatic equipment similar to Fig. 7 was installed just before the war. Shortly after it was fitted, the filament in the main 150-watt lamp broke down in the middle of a very urgent operation. The three 40-watt emergency lamps came into operation instantly and the surgeon was able to complete the operation. At a London cinema, owing to a fault in a transformer the whole supply to the cinema was interrupted, but the emergency lights, which were on the floating-battery system, remained on, and the staircases and gangways and exits were all adequately lighted.

A simple form of equipment was introduced about 1932, intended for places where the lowest possible expenditure with battery supply was required. It comprised a 12-volt portable battery, which supplied the current to the emergency lamps when required. The difficulty was the switching on by hand of the emergency lamps; to bridge the interval of temporary helplessness when a room is plunged into total darkness, a very small 12-volt lamp was fixed as a guide alongside the switch for the emergency lights. Battery charging was not difficult; the battery was taken away to be charged, or a small rectifier was coupled in the circuit and switched on with the main lights.

Mr. Harold Bright: It may be of interest to mention the results obtained in practice with an emergency lighting installation in an important hospital in the centre of London where there have been nine failures of supply during air raids. The hospital has alternative supplies from both the a.c. and d.c. networks, but on some occasions both supplies failed. During at least three of those failures important operations were being carried on. The emergency lighting was installed before the war to supply the operating-theatre suites, and was then extended to all staircases and some corridors. The equipment was installed on the top floor and on one occasion was severely shaken by blast, all the cells being moved and twisted on the stands, but it continued to work.

Since it was considered desirable to give the battery in that installation a small amount of regular work to do, the whole of the impulse clocks in the hospital are supplied from it. This probably results in the battery receiving a little more attention than it would otherwise do, for it gives a warning of failure which everyone can see.

The installation was put in 12 years ago and was one of the first to incorporate a combined method of charging, i.e. a metal rectifier is used for the trickle-charge on the score of cheapness, simplicity and high efficiency, but for quick charging a hot-cathode valve is used, this being cheaper than a metal rectifier of the same output.

I agree with the author that in operating theatres the emergency lighting should be comparable in intensity and distribution with the main lighting, instead of being only a small fraction of it.

An application of emergency lighting equipment which is not mentioned in the paper, but which may be of importance again after the war, is for dog-racing tracks, where a failure of lighting might be very serious, and indeed lead to conditions of panic.

Mr. E. J. MacWilliams: As a user I have found "Keepalite" systems very satisfactory; undoubtedly they reduce to a minimum the maintenance of any emergency lighting system. A

previous speaker mentioned the value of these equipments in operating theatres, and I can confirm his experience.

The author has referred to 2-pole switches which control simultaneously the main and emergency lighting. I have introduced that system in several instances, and I think it is a very good one, because in an emergency one wants the battery to last as long as possible.

In my own experience, I have found that theatre lighting and hospital lighting generally should be made as automatic as possible, i.e. not only bringing in the emergency lighting when the main supply fails, but also disconnecting it when the supply is restored.

We always speak of low voltages—12, 24 or 50 V—for these emergency supplies. These low voltages may have originated for economic reasons, a low-voltage battery costing much less than one of double the voltage, but I wonder whether they have been brought about by the Zeiss type of double-filament lamp. I think that lamp is excellent, but it is a pity that it has such a very low-voltage emergency filament. In dovetailing a new emergency system into existing lighting circuits, I have found the very low voltage to be a nuisance; it appears that the extra cost of the higher-voltage battery might be worth while.

Mr. P. S. Cattle: I should like to hear a few words from the author as to the maintenance and simplicity of these equipments. The average client regards with awe a number of glass boxes with a gassy smell. The author says that ventilation of the cells is necessary, but an equally important point is to avoid dry air, which has often caused trouble in basements near the boiler room. It is desirable to maintain a normal temperature of about 60° F, to avoid sunlight, to use acid-proof paint on floors, and to ensure cleanliness. The keeping of proper records is also important.

I agree with the author that, where large numbers of people can collect in a confined space which is artificially illuminated, some source of secondary lighting is called for to indicate stairs, doors and other obstructions.

I should like the author to give us an outline of the probable future of batteries, bearing in mind the universal use of alternating current and the ubiquity of the Grid. All sorts of automatic devices are made for a.c. only, so that we may have to get a.c. from the battery or find some other means of dealing with the situation. There may be a possible future for batteries installed in buildings to take care of the peak load and to store energy during the night. They might also be used for signal systems and calculating machines.

In the diagrams in the paper, wherever automatic switches are shown, "a.c." is at the top and "d.c." at the bottom; I think that is wrong, because the arc will rise and may short-circuit the a.c. supply. It is in parallel or in series, according to the sine wave. If it is in series, I think that with some contactors there will be trouble.

During the war I have found it very useful to install small dry-charged accumulators as standby in banks, substations, etc., filling them up as they are wanted. There is another use for batteries meriting reference. I have known cases where the voltage has risen by 10–15%; here I have installed contactors controlling batteries which cut in and out when the voltage rises and falls by this percentage, the battery being locked into circuit until the voltage of the main supply becomes stable again for a predetermined period.

Mr. S. A. Stevens: I propose to confine my remarks to the charging of batteries. The author has shown how the development has aimed at making the charging system as automatic as possible. In a cinema, the lighting load is very constant once the performance has started, when the output of the rectifier can be maintained slightly above the load, even though controlled by hand as in Fig. 2. There are, however, many other uses of standby plants where the load is not constant, and where a floating system with hand tapping would be impossible.

The system in Fig. 1, using the floating generator set, gives what is wanted, but as it uses a piece of rotating apparatus requiring attention it cannot be left unattended for long periods.

Fig. 3 at first sight might appear to be the equivalent of static apparatus; this is not so, because it does not compensate for primary-voltage variations, but, in fact, exaggerates them.

I think the author has made a rather weak excuse for accepting these variations, by suggesting that the battery voltage can vary within reasonable limits without appreciably altering the state of charge; in any case, this variation in battery voltage must appear as a variation in load voltage. The compensating windings, too, of this system are in series with the output from the battery, so that on a mains failure not only is there the normal drop in battery voltage due to the change from floating-battery condition to discharge condition, but there is also the resistance drop in windings 4 and 5. The magnification of mains-voltage variation and this nuisance of additional resistance drop were found such serious objections to numerous modifications of this circuit, that work on developing these schemes was abandoned.

Moreover, these load-current compensating schemes require manual attention should the supply fail and the capacity of the battery be called upon, because without manual adjustment they will not recharge the battery when the main supply is restored.

Just before the war we were developing a completely different and truly-constant voltage floating scheme which did not have these objections; it permitted the battery to be directly connected to the load, gave full compensation for mains-voltage variation, and also provided automatic recharge of the battery, even after a prolonged mains failure. The war prevented its use for the original cinema application, but many other uses have been found for it, particularly in communication work. It is a system which provides a compounding of the output of the rectifier; on the input side there is a split-phase arrangement which on full load converts from single-phase to two-phase, while the secondary windings of the transformer are so connected as to convert from two-phase to three-phase, so that on full load the rectifier functions as a full-wave, three-phase, bridge-connected rectifier. At lighter loads, the arrangement is so proportioned that the phase displacement alters both in angle and in magnitude; at no-load, the rectifier functions as a single-phase bridge. The degree of variation from single-phase to three-phase can be controlled by tappings on transformers. This arrangement can be made fully automatic. If the battery voltage has fallen owing to discharge of the battery, the output of the rectifier, being level-compounded or slightly drooping-compounded, rises correspondingly to recharge the battery, and if the size of the charging plant is correctly chosen, it can safely be left to look after the state of the battery under floating conditions, and to recharge the battery after a mains failure, without any adjustment whatever.

Mr. R. V. M. Shinnie: It would be interesting to hear the author's opinion regarding the effects of trickle-charging and floating, upon batteries and particularly on the life of the positive plates. It seems that both trickle-charging and floating, when the charge rate is probably only 10% of the normal, tend to promote the formation of spongy lead and in so doing swell the paste on the positive plates. I have known instances of celluloid-cased cells which had been put into wooden box containers and, later, could not be withdrawn for recharging or for change of acid.

Concerning batteries for standby work, one point must be borne in mind. A certain 50-cell battery with only one positive and one negative plate per cell developed a fracture between the top of one of the plates and the terminal lug, just above the

electrolyte. This caused a violent explosion of the cell due to the hydrogen gas normally present; this danger must be guarded against where batteries of high voltage and small ampere-hour capacity, especially portable, are subjected to vibration. I have not experienced this trouble in car batteries, but these have a number of plates to maintain the circuit.

Mr. T. S. Pick: The paper deals with emergency lighting systems with particular reference to battery equipments, but is that the whole story? To-day it is a case of buildings far below and far above ground with fans, pumps and transport. These require alternating current—not direct current—in rather large quantities. Almost all the supply comes from the Central Electricity Board, and it would be interesting to know what can act as an alternative supply.

THE AUTHOR'S REPLY TO THE DISCUSSION

Mr. S. H. Chase (*in reply*): I agree with Mr. Raphael that for a long time the advantages of emergency-lighting equipment were not fully appreciated. But considerable progress has been made during recent years, and an adequate and efficient system is now usually included in the specifications of new buildings of the types covered by the paper. I believe the duplicate operating mechanism he mentions refers to the duplicate contactor arrangement shown in Fig. 10, which may now be obsolescent in view of B.S. 764.

A mains-voltage safety circuit is probably the best for cinemas.

I agree on the electrical unsuitability of existing types of three-terminal, low-voltage, twin-filament lamp. Four terminals would be better. Optically, twin filaments may offer advantages.

The modern type of switch relay is usually of the sunk pattern and can be made flash-proof, as could also the two-way switch in Fig. 9.

In the three-phase contactors, the contact arms on each side form one mechanical unit so that all on one side either break or make at the same time. Normally, the alternating current has failed before the switch operates, and in any event the parallelling of the three-phase wires on the d.c. side occurs only after the live a.c. supply has been properly disconnected. Numbers of these switches are installed, and to the best of my knowledge they have given no trouble.

I can fully endorse Mr. Bright's remarks as to the effect of blast on batteries, and know of a number of cases where the buildings housing them have been badly damaged and the batteries in glass containers have remained intact and continued to function.

It is inadvisable to connect any load to a standby battery except the emergency one.

In reply to Mr. MacWilliams, the low voltages for emergency supplies were chosen mainly for economic reasons.

In reply to Mr. Cattle, a short experience of modern trickle-charging quickly dispels the old idea that a battery is a trouble, since the routine charge and discharge (and consequent early renewals), regular topping up and frequent recording of gravities, are all eliminated. Section 8 indicates the simple procedure to be adopted to maintain the battery in first-class condition, and occasional testing of the contactor is all that is necessary to ensure its correct working.

Both Mr. Cattle and Mr. Pick refer to the provision of an a.c. supply. Where it is required for emergency power services and some types of lighting, an immediate supply is available from a battery utilizing running machinery. Future developments may enable this to be done statically. It is rare that other than skeleton services of this type are required during an emergency. New and better types of batteries will be produced.

Experiments with all types of automatic switches have shown that the design of those illustrated, particularly for moderate currents and voltages, provides the simplest and most effective method of ensuring that the switch will fall into the safety position in the event of a failure.

Change-over contactors above a certain capacity now have the d.c. break at the top, in accordance with B.S. 764.

I am aware of the constant-voltage floating scheme referred to by Mr. Stevens, but lack of space limited reference to only one such system. I believe I selected the one most used in cinemas, which, though not having perfect compensation for a.c. voltage variations, has yet proved to be a considerable improvement on a simple rectifier.

Section 8 answers most of Mr. Shinnie's remarks. A trickle charge of 10% of the normal charging rate is far too much and will cause trouble. To maintain a standby battery in a fully-charged and healthy condition, the correct rate is usually less than 1% of the normal charging rate.

INSTRUMENT TRANSFORMERS*

By A. HOBSON, B.Sc.Tech.(Hons.), Associate Member.†

(*The paper was first received* 18*th November*, 1942, *and in revised form* 20*th July*, 1943. *It was read before the* MEASUREMENTS SECTION 19*th November*, 1943, *and before the* NORTH-EASTERN CENTRE 13*th March*, 1944.)

SUMMARY

The paper is in three Sections.

Section 1 describes a new method of reducing current-transformer errors, using a compensator which may be either an integral part of the current transformer or a separate unit for use with an existing transformer. The compensator employs normal design principles and does not depend on highly critical conditions such as saturated cores.

Very high accuracies are obtained, and standard transformers may be constructed having almost unmeasurably small errors over the whole current range, using the most sensitive testing equipment.

In Section 2 a method of testing voltage transformers is described in which the Arnold current-transformer equipment may be adapted for this purpose. The set measures the difference in error between a standard and the test transformer.

Section 3 deals with the estimation of the errors of three-phase star-to-star voltage transformers at their working burdens, from the results of tests at unity-power-factor burdens. Two methods are given: the first uses the six phase-neutral test results usually provided by manufacturers; the second, in which no three-phase calculations are involved, uses the results of 12 special tests if three phases are to be loaded or of 6 tests if only two phases are to be loaded.

(1) INTRODUCTION

The primary winding of a current transformer is connected in series with the line carrying the current to be measured, and, since the impedance of the transformer is in general very small compared with that of the rest of the system, it may be said that for all practical purposes the line current is unaffected by changes in the transformer.

The secondary winding is connected to a fixed impedance comprising one or more instrument current coils, and a current flows in this circuit such that the primary and secondary ampere-turns are sensibly equal in magnitude and opposite in phase position. An ideal current transformer may be defined as one in which the primary and secondary currents maintain their exact nominal ratio and are in precise phase opposition for all operating conditions. Neglecting for the moment minor factors such as change of temperature, etc., the main changes to be expected are changes in supply frequency, burden impedance and line current.

For a normal transformer such as is used in supply metering, the frequency and burden impedance are constant, and the definition of an ideal transformer may be reduced to one in which the primary and secondary currents maintain their exact nominal ratio and are in precise phase opposition for all primary current values within the required range of measurement.

Actual transformers do not conform to the ideal, the principal reason being that an e.m.f. is needed to force the secondary current through the total impedance of the secondary circuit. In consequence a certain amount of magnetic flux is necessitated in the core, and the magnetizing and iron-loss ampere-turns required to maintain this flux subtract vectorially from the primary input ampere-turns. The result is that the secondary ampere-turns are less in magnitude and are not in exact phase opposition to those of the primary, thus causing the transformer to have ratio and phase-angle errors.

Since the impedance of the secondary circuit is constant the e.m.f. in this circuit, and consequently the flux density in the core, is sensibly proportional to the primary current. Owing to the non-linearity of the magnetizing and iron-loss curves of core iron, however, the errors of current transformers vary considerably when the primary current is changed. It is this fact which presents the greatest difficulty in calibrating supply meters with current transformers.

When considering the problem of producing current transformers without errors the obvious procedure is to try to make up the magnetizing losses either by feeding corrective ampere-turns to the transformer by means of a third winding, or corrective current direct to the secondary circuit.

This is, however, a most difficult task, since the amount of correction required at different primary currents varies not only in magnitude but also in phase position according to complex laws. In spite of this, a number of methods of compensation employing these principles have been put forward, the most notable example being that due to Wellings and Mayo,[4] but owing to the extreme difficulties involved the measure of success attained has been limited.

The author has investigated the problem from another angle, namely that of injecting into the secondary circuit the e.m.f. required to force the current through the impedance of that circuit. When this is done properly no e.m.f. needs to be induced in the transformer secondary; consequently the core flux is zero and the transformer operates without either ratio or phase-angle error. Moreover, the required e.m.f. is directly proportional to the primary current and maintains the same phase position, offering a very simple problem when compared with the provision of magnetizing ampere-turns.

(1.1) Operation of Compensator

In the present method the compensating e.m.f. is obtained from an auxiliary current transformer operated by the same primary current as the main current transformer.

The principle of operation may be understood by a reasoned consideration of Fig. 1, representing diagrammatically the arrangement for a 500/5-amp ring-type transformer. Numerical values have been assigned to the various quantities for purposes of clarity. The main secondary winding is A, which has its

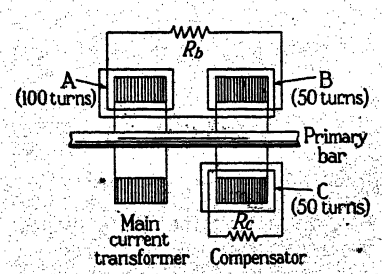


Fig. 1.—Arrangement of windings in compensated transformer.

* Measurements Section paper. † F. C. Smith and Co. (Transformers), Ltd.

nominal 100 turns, while windings B and C on the compensator have 50 turns each. The transformer burden R_b is 0·2 ohm, corresponding to 5 VA at 5 amp, and R_c may be termed the compensating burden. For convenience R_b and R_c are taken as non-inductive and the whole apparatus is assumed to operate ideally so that resistances of windings, core losses and magnetizing ampere-turns are considered to be zero. Relative directions of currents are shown by arrows.

First consider the conditions obtained when the primary current is 500 amp and R_c is zero. The current in the main secondary circuit, i.e. in windings A and B and in the burden R_b will be 5 amp, this value being decided solely by the number of turns on winding A. It will be appreciated that winding B does not constitute an impedance in the path of the secondary current owing to the presence of the closed winding C on the same core. The ampere-turn balance on the compensator core is maintained by a current of 5 amp flowing in winding C, and it is clear that this current and the main secondary current are in phase with each other and in phase opposition to the primary current.

Since R_c is assumed to be zero no e.m.f. is needed to cause current to flow in winding C; consequently the flux in the compensator core is zero and no e.m.f. is induced in winding B. A total e.m.f. of 1 volt, in phase with the current, must be induced in windings A and B in order to overcome the burden resistance of 0·2 ohm. In the present case the whole of this e.m.f. must be induced in A and a corresponding magnetic flux is set up in the main core which in a practical transformer would cause normal ratio and phase-angle errors. Under this condition the compensator has no effect on the performance.

Next consider the effect of steadily increasing R_c. An e.m.f. proportional to R_c and in phase with the current must now be induced in winding C, and to accomplish this a flux must be set up in the compensator core. The turns of winding B also link this flux, and in consequence an identical e.m.f is induced in this winding, since B and C have the same number of turns. The e.m.f. in B is in phase with the current, and, because the total output of A and B must remain at 1 volt, it follows that a reduced e.m.f. is required from A. The consequent reduction in the main core flux would in a practical transformer cause a reduction in the ratio and phase-angle errors.

When $R_c = 0{\cdot}2$ ohm the e.m.f.'s induced in B and C are each 1 volt. Under this condition winding B supplies the whole of the e.m.f. needed for the secondary circuit, and none whatever is induced in A. As a result the main core flux is eliminated and in a practical transformer the errors due to magnetization losses would disappear entirely. If R_c were greater than 0·2 ohm the e.m.f. induced in B would exceed 1 volt, and to keep the total secondary output at 1 volt a negative e.m.f. would be induced in A. In consequence the transformer would be over-compensated and would in the practical case show errors of the opposite sign to those normally experienced, i.e. a positive ratio error and a negative phase angle.

A brief consideration shows that the value $R_c = 0{\cdot}2$ ohm gives complete compensation for all line currents, as all the currents and e.m.f.'s are proportional to the primary current.

If the burden resistance were replaced by an impedance Z_b the e.m.f. required for the secondary circuit would be changed in magnitude and phase position. It is clear that complete compensation would then be obtained by substituting for R_c an impedance identical in magnitude and power factor with Z_b.

In the above example the compensating burden is equal to the secondary burden. By adjustment of the ratio of the ampere-turns in windings B and C the auxiliary burden may be made to have any desired value (Appendix 5.1).

Winding C need not, of course, be a 5-amp winding. If in the present case it were wound with 250 turns, for instance, the current in the compensating circuit would be 1 amp and R_c would be 5 ohms in the ideal case, the watts dissipated remaining unaltered.

(1.2) Actual Transformers

In practice account must be taken of the factors which cause the performance to fall short of the ideal. Chief among these are the resistance and leakage reactance of the windings and the magnetizing and iron-loss ampere-turns needed to maintain the flux in the compensator core.

The compensating e.m.f. must overcome the impedances of windings A and B in addition to the secondary external burden, so that in practical calculations Z_b should include the whole of the impedance of the secondary circuit. Similarly the compensating impedance includes the total impedance of the compensating circuit.

Regarding the magnetization losses, the compensator may be considered as a current transformer having C as its secondary winding. The current in winding B is almost exactly proportional to, and in phase opposition to, the primary current, so that the effective input ampere-turns of this current transformer are very nearly the difference between the primary ampere-turns and the *nominal* ampere-turns of B.

Owing to the errors of this transformer the current in C is slightly less than its nominal value, and is not in precise phase opposition to the primary current. In consequence, if the exact calculated value of auxiliary burden is used the compensating e.m.f. is also incorrect in magnitude and phase position by the same relative amounts. The result is that a small voltage has to be induced in A to make up the difference, and the main current transformer shows small errors. These errors are of the same order of magnitude when compared with those of the uncompensated transformer, as the loss ampere-turns in the compensator core compared with the total ampere-turns of winding C.

By a slight adjustment of the compensating burden these errors may be reduced to zero for any one value of primary current. For other primary currents the compensating e.m.f. should maintain its phase position and vary in exact proportion. The errors of the auxiliary transformer change, however, as the primary current is changed, and the compensation will not therefore be exactly correct for other current values. If the change of error is 1%, for instance, the compensating e.m.f. will be 1% out, and as a result the main current transformer will have errors of the order of 1% of the uncompensated errors.

It is apparent that the accuracy of the main current transformer is a function of the accuracy of the compensator, and, since the latter always works on something less than half the primary ampere-turns, its errors are always greater than the natural errors of the main current transformer. It is also apparent that compensation will be relatively less effective the lower the available ampere-turns, and that ring-type transformers of low ratio will be the most difficult to compensate.

In spite of this, very good results are obtained as will be shown later. When the compensation is applied to standard transformers having 500 ampere-turns or more the errors are so small that they are difficult to detect.

(1.3) Effect of Change in Burden

For a given value of primary current the compensator injects a fixed e.m.f. into the secondary circuit, this e.m.f. being largely unaffected by changes in the main burden Z_b. For one value of Z_b complete compensation is obtained, and this will usually be arranged to be the normal working burden. If the burden is changed the e.m.f. induced in B no longer has the exact value

required and the difference must be induced in A, which necessitates a magnetic flux in the main core proportional to the change in burden. If the burden is increased the transformer will be under-compensated, and will therefore have a negative ratio error and a positive phase angle. If the burden is decreased the transformer will be over-compensated and will have a positive ratio and a negative phase angle.

Change of burden power factor has a similar effect, and this is shown vectorially in Fig. 2, in which E is the total e.m.f. required and E_B that induced in B, E_A being the difference to be induced in winding A. The resulting flux in the main core is Φ and the magnetizing current is I_m. In this particular case it is seen that the transformer has a negative ratio error and a lagging or negative phase angle.

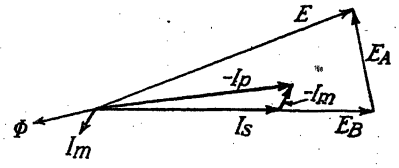


Fig. 2.—Effect of change of burden power factor on errors of compensated transformer.

E = required secondary e.m.f.
E_B = e.m.f. induced in winding B.
E_A = e.m.f. induced in winding A.
I_s = secondary current.
I_M = magnetizing current.
I_p = primary current.
Φ = flux in main core, due to E_A.

The magnitude of the errors incurred in this way is roughly the same fraction of the uncompensated errors as the fractional change in burden. For instance, a transformer compensated for 15 VA (including the internal burden of the windings), and used on 12·5 or 17·5 VA, would have errors of the order of one-sixth of the uncompensated errors.

(1.4) Magnitude of Compensating Burden

This burden represents an additional impedance in the line, and it should on that account be as small as possible. Provided, however, that its magnitude does not exceed a reasonable fraction, say one-half, of the normal impedance of the transformer its actual value is of no great moment.

From Appendix 5.1 the volt-amperes in the compensating burden are given by multiplying the fraction (Ampere-turns in C)/(Ampere-turns in B) by the total volt-amperes in the main secondary circuit.

It is seen that reduction of the volt-amperes may be accomplished by reducing the ampere-turns of winding C, the compensator errors being increased thereby. Since, however, first-order errors in the compensator produce only second-order errors in the main secondary current it is possible to reduce the auxiliary burden considerably without appreciable deterioration of the overall performance.

In practice the volt-amperes in the compensating burden vary from about 5 to 100% of the main burden, depending on the type of transformer.

It should be borne in mind that in many cases a compensated transformer will have less total impedance than a normal one of the same order of accuracy, owing to the reduction of operating ampere-turns made possible. Particularly is this so in precision current transformers, the secondary windings of which often constitute the greater part of the total burden.

(1.5) Effect of Change of Frequency

In testing stations standard transformers may be required to work on various frequencies, and it is preferable that changes in operating frequency should not result in appreciable changes in error.

In the ideal case a compensated transformer is correct for all frequencies, the only effect of changes being to vary the flux density in the compensator core. In practice this variation of flux causes a change in the errors of the compensator, and second-order errors are consequently introduced into the main secondary current. Precision transformers show scarcely any variation due to changes of frequency between 25 and 100 c/s, the usual limits in a.c. supply.

(1.6) Other Sources of Error

Up to the present time the magnetizing losses have in general been considered the sole source of current-transformer error. In a compensated transformer the effect of these losses is reduced to a negligible value and consequently it becomes necessary, especially in the case of precision transformers, to consider sources of error which would justifiably be neglected in a normal transformer. Chief among these are changes in ambient temperature, self-heating, magnetic leakage and inter-turn capacitance.

Errors due to variations in atmospheric temperature and self-heating may be considered together. The secondary circuit of a current transformer comprises the winding, leads and instrument coils, and all these normally consist of copper. They will all be subjected to different temperature rises due to self-heating, but an average figure of 20° C may be taken for the whole circuit. The temperature of a test room in this country is unlikely to vary by more than 10 deg from the mean of 15°, so that the maximum change in the temperature of a current transformer due to both causes would be of the order of 30 deg.

This would have a negligible effect on the magnetic characteristics of the core, but would increase the resistance of the secondary circuit by about 12%. If the resistance of the compensating circuit remained unaltered the transformer would show errors of the order of 12% of the uncompensated errors. For instance, a transformer having a natural phase angle of 2 min, and compensated to give zero errors at 15° C, would have an error of about 0·25 min on a hot summer day after, say, two hours on full load. Only measurements of extreme precision would be noticeably affected by such a small error.

Where necessary, however, such changes in performance may be eliminated by a variable impedance in the compensating circuit; this also enables adjustments to be made for varying secondary burdens.

Another method of eliminating temperature errors is to make the whole of the compensating circuit of copper, so that its resistance also changes with temperature. The effects of ambient temperature are by this method completely eliminated, and if the temperature/time constant is arranged to be substantially the same as that of the main secondary circuit the effects of self-heating will be reduced to a negligible value.

Leakage flux in current transformers is superposed on the working flux, causing a change in the ampere-turns needed to set up the working flux and a consequent change in the ratio and phase-angle errors of the transformer.

In a compensated transformer the working flux in the main core is reduced practically to zero, and it follows that a normal amount of leakage flux will have a negligible effect on the errors. The errors of the compensator may be appreciably affected, however, and small errors may in consequence be introduced into the main secondary current; these errors will be of the second order compared with the uncompensated errors.

Transformers with fixed primary windings may readily be compensated to allow for the effect of leakage by a small adjustment of the compensating burden. Ring-type transformers,

however, are often used for different ratios by winding primary turns through the central aperture, and where the number of turns is very few it is practically impossible to obtain uniform distribution.

Dr. A. H. M. Arnold[3] and Price and Duff[8] have investigated this point and their results are fully discussed in pages 127–138 of Dr. B. Hague's book on "Instrument Transformers."[1] It is shown that for a transformer having a uniformly distributed secondary winding the arrangement of the primary turns has very little effect where the ampere-turns are 2 000 or less. In general the ampere-turns of compensated transformers of normal ratios will not exceed this figure, so that leakage effects, being reduced to a fraction of their former value, need not be considered.

Above 5 000 ampere-turns, however, Dr. Arnold found that very large increases of ratio error, and much distortion of wave form, were obtained if the primary turns were concentrated on one part of the core; a 20 000-ampere-turn transformer showed a ratio error of no less than 67%.

These effects were due to saturation of parts of the Mumetal core on account of the high number of ampere-turns involved, and, while compensation would probably reduce the overall error considerably, extreme precision would not be obtained. Dr. Arnold has, however, described in his paper the construction of a copper shield which reduces the effects of leakage to a very small value.

Comparatively little information is available regarding the effects of self-capacitance of windings on the performance of current transformers. The author's experience is that these effects are negligible unless the number of turns on either winding is of the order of 5 000 or more, a condition only obtained in precision transformers of very low ratio, say 0·5/5 amp or less. In one case a variation of 0·01% in ratio and about 1 min phase angle were observed on a transformer having a primary winding of 8 000 turns.

In a compensated transformer the errors may be reduced to zero by a slight adjustment of the auxiliary burden, any effect of capacitance thus being eliminated. It is reasonable to suppose that capacitance effects for a given current transformer will be proportional to the current and that in consequence one value of compensating burden will be correct for all primary currents.

(1.7) Use of "Pre-magnetization"

The errors of most current transformers may be considerably reduced by the application of pre-magnetization. This artifice has appeared in several forms during the last thirty years but the underlying principle is the same in all cases.

Briefly the idea is to use additional a.c. magnetization to pre-excite the core to a flux density in the region of maximum permeability, and to superimpose the working flux on this. The normal working flux density of a current transformer rarely exceeds 2 000 gauss, and the permeability of iron at such densities is relatively low. Pre-magnetization puts the iron into a better magnetic condition before the working flux is applied, and a marked reduction in the ampere-turns needed to maintain this flux is the result.

The additional magnetization may be obtained in several ways, three of which are illustrated in Fig. 3, (*a*) from a separate source

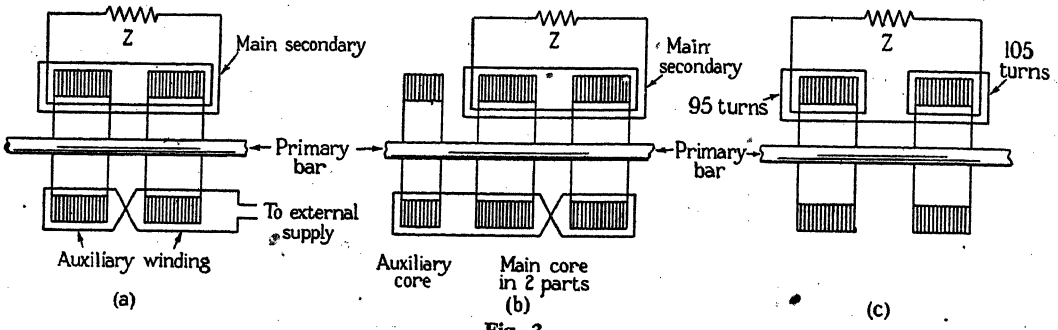


Fig. 3

(*a*) Pre-magnetization obtained from external source. (*b*) Pre-magnetization from an auxiliary current transformer.
(*c*) Pre-magnetization by unbalanced magnetization force on two halves of main core. Nominal ratio 500/5 amp; number of turns = 100.

such as the secondary of a voltage transformer,[7] (*b*) from an auxiliary current transformer,[4] and (*c*) by some special arrangement of the transformer's own secondary winding.[14] In each case the main core is split in two equal parts which are pre-magnetized in opposite directions so that no resultant e.m.f. due to the extra magnetization is induced in the secondary circuit.

It is to be expected that, when properly applied, method (*a*) will give the best results because the auxiliary excitation is constant and may therefore be arranged to maintain its most beneficial value at all loads. In practice the provision of a voltage transformer for this especial purpose is rarely worth the improvement obtained. The method should, however, find some practical application in high-voltage metering, since its use may enable simple bushing transformers to be employed where costly wound-type transformers would otherwise have been essential. In such installations a voltage transformer is required in any case to energize the meter potential coils, and the auxiliary excitation may be obtained from this. The extra burden on the voltage transformer is only a few volt-amperes, and does not affect the errors to any appreciable extent.

Methods (*b*) and (*c*) have the advantage that the current transformer may be constructed as a self-contained unit with no external complications. The amount of pre-magnetization obtained, however, varies with the line current, and consequently the maximum advantage is not maintained for all values of primary current. For example the auxiliary flux density in a Stalloy transformer may vary from 1 000 to 10 000 gauss as the current changes from 10% up to 150% of its rated value. It is often found, in fact, that the errors at the higher currents are adversely affected, because the auxiliary flux density is well above the point of maximum permeability.

The benefit obtained by pre-magnetization is generally better the lower the working flux density. For this reason it appears that some form of this device should be particularly useful when combined with the author's method of compensation, since by this means the working flux is already reduced to a very small value.

One set of figures showing the effect of this combination is given in the tables of results, but investigations are not yet completed in this field.

(1.8) Test Results

Tables 1 to 5 give figures showing the effect of compensation on the errors of three ring-type current transformers.

Table 1

TRANSFORMER NO. 1: 500 AMPERE-TURNS, MUMETAL CORE, WEIGHT 7 LB

Rated current	Uncompensated		Compensated for 5 VA (non-inductive)							
	5 VA		5 VA		2·5 VA		7·5 VA		5 VA, 0·8 P.F.	
	Ratio	Phase	Ratio	Phase	Ratio	Phase	Ratio	Phase	Ratio	Phase
%	%	min	%	min	%	min	%	min	%	min
100	− 0·042	+ 4·0	0·000	0·00	+ 0·025	− 1·9	− 0·027	+ 1·9	− 0·047	− 1·3
60	− 0·053	+ 4·9	0·000	0·00	+ 0·023	− 2·1	− 0·024	+ 2·1	− 0·050	− 1·3
20	− 0·068	+ 5·6	+ 0·001	+ 0·04	+ 0·019	− 2·4	− 0·021	+ 2·5	− 0·060	− 1·2
10	− 0·077	+ 7·3	+ 0·002	+ 0·06	+ 0·024	− 2·5	− 0·017	+ 2·6	− 0·058	− 1·3

Table 2

TRANSFORMER NO. 1

Rated current	Uncompensated		Compensated for 25 VA (non-inductive)					
	25 VA		25 VA		22·5 VA		27·5 VA	
	Ratio	Phase	Ratio	Phase	Ratio	Phase	Ratio	Phase
%	%	min	%	min	%	min	%	min
100	− 0·297	+ 6·8	+ 0·005	0·00	+ 0·029	− 1·7	− 0·024	+ 2·4
60	− 0·320	+ 8·1	+ 0·003	0·00	+ 0·027	− 2·0	− 0·024	+ 2·1
20	− 0·318	+ 15·7	+ 0·013	+ 0·21	+ 0·030	− 2·2	− 0·012	+ 2·7
10	− 0·273	+ 19·2	+ 0·021	+ 0·35	+ 0·042	− 2·2	0·000	+ 2·9

Table 3

TRANSFORMER NO. 2: 500 AMPERE-TURNS, STALLOY CORE, WEIGHT 8 LB

Rated current	Uncompensated		Compensated for 5 VA (non-inductive)					
	5 VA		5 VA		2·5 VA		7·5 VA	
	Ratio	Phase	Ratio	Phase	Ratio	Phase	Ratio	Phase
%	%	min	%	min	%	min	%	min
100	− 0·36	+ 29	− 0·110	0·0	+ 0·114	− 15	− 0·240	+ 15
60	− 0·40	+ 38	− 0·160	+ 0·9	+ 0·115	− 17	− 0·275	+ 19
20	− 0·440	+ 59	− 0·076	+ 5·3	− 0·220	− 22	− 0·406	+ 29
10	− 0·530	+ 76	+ 0·024	+ 9·7	− 0·270	− 25	− 0·340	+ 37

Table 4

EFFECT OF PRE-MAGNETIZATION ON NO. 2 TRANSFORMER

Rated current	Compensated for 5 VA (non-inductive)					
	5 VA		2·5 VA		7·5 VA	
	Ratio	Phase	Ratio	Phase	Ratio	Phase
%	%	min	%	min	%	min
100	− 0·057	0	+ 0·195	− 11·0	− 0·305	+ 11·5
60	− 0·092	− 0·3	+ 0·080	− 9·5	− 0·275	+ 9·2
20	− 0·050	− 0·3	+ 0·090	− 7·8	− 0·180	+ 8·1
10	− 0·015	+ 4·8	+ 0·055	− 9·5	− 0·120	+ 17·8

Table 5

TRANSFORMER NO. 3: 50/5 RING TYPE, MUMETAL CORE, WEIGHT 10 LB

Rated current	Uncompensated		Compensated	
	2·5 VA		2·5 VA	
	Ratio	Phase	Ratio	Phase
%	%	min	%	min
100	− 1·50	+ 35	+ 0·15	+ 5
60	− 1·55	+ 50	0	0
20	− 1·40	+ 83	+ 0·23	+ 8
10	− 1·25	+ 100	+ 0·45	+ 13

The true criterion of the effectiveness of compensation is a comparison of the results obtained (*a*) with the compensated transformer and (*b*) with the normal transformer of the same nominal ratio employing the whole of the core iron used in (*a*). Accordingly each of the transformers tested was dismantled and the two cores assembled together and re-wound as an ordinary transformer.

All the measurements were made on an Arnold type testing equipment,[2] the available standard transformer having a ratio error of 0·01% and a maximum phase angle of 0·36 min.

These errors, although very small in themselves, were much too large to test transformer No. 1 by a comparison method. This transformer was accordingly wound for a ratio of 5/5 amp and tested by the direct method given by Dr. Arnold in his paper.

Transformer No. 1 had a Mumetal core weighing a total of 7 lb and was wound with 500 ampere-turns. The core was of the clock-spring type, magnetic path 25 cm, thickness of material 0·015 in, and the Mumetal was taken at random from stock. Table 1 shows the errors at 5 VA with and without compensation. The effects of varying the burden by 2·5 VA in either direction, and of changing the burden power factor to 0·8, are also shown. Table 2 gives the errors of the same transformer at 25 VA. It should be noted that the variation in error for a change in burden of 2·5 VA is about the same in both tables.

Transformer No. 2 was almost identical in construction with No. 1, but the core was of Stalloy. Results are given in Table 3.

In Table 4 the combined effect of compensation and pre-magnetization on No. 2 transformer is shown. Comparing these figures with those in Table 3 it is seen that not only are the actual errors halved, but the variation in error due to change in burden is also much reduced.

The accuracy attained at the actual compensated burden is within the limits of Class AL. It is believed that still better figures are obtainable.

Transformer No. 3 had a ratio of 50/5 amp. The core was stock 0·015-in Mumetal of the same diameter as No. 1, but weighing 10 lb.

(1.9) Practical Applications

(1.9.1) Standard Precision Transformers.

The smallest errors hitherto obtainable by normal design are of the order of 0·005% ratio and 0·5 min phase angle. Transformers having errors of this magnitude must employ a very large number of ampere-turns, often as many as 5 000, and specially selected Mumetal cores of large diameter and weight to accommodate the great amount of copper required. It is possible to reduce the phase error of a transformer to zero by connecting a condenser across the secondary or a specially provided tertiary winding. The slope of the phase-angle curve is not, however, affected by this device, and zero error may only be obtained for one value of primary current using a given condenser.

The figures in Table 1 show that by using compensation extremely small errors may be obtained with as few as 500 ampere-turns and a stock core weighing only 7 lb. Using the most sensitive range of the Arnold testing equipment the phase angle of transformer No. 2 was almost unreadably small over the whole range of measurement. A variation of 2·5 VA from the compensated burden caused errors of 2 to 3 min, but in many cases precision transformers are always used on the same burden, and this variation is therefore not important under such conditions.

The errors of a current transformer are, very approximately, proportional to the inverse square of the ampere-turns. Compensated transformers having, say 2 000 ampere-turns accordingly have errors completely negligible even judging by the highest of present standards, and the change in error due to variation in burden is much less than that shown in Table 1. Tests were carried out on a compensated transformer having 2 000 ampere-turns and a stock Mumetal core of 0·015-in material weighing less than 8 lb. This transformer was first compensated for 7·5 VA and then tested at 5 VA, 7·5 VA and 10 VA at three frequencies, 25, 50 and 100 c/s. At the compensated burden the phase angle was zero over the whole current range at all frequencies, while the ratio error was 1 part in 100 000. This error could probably have been eliminated by a slight variation of the power factor of the compensating burden.

It is therefore possible to construct transformers having negligible errors much more economically than hitherto. If a transformer is to be used with more than one burden it is a reasonably simple matter to arrange a variable compensation.

It is also possible to construct compensators as entirely separate units to be used with existing transformers. No technical or practical difficulty is experienced in doing this, the primaries and secondaries of transformer and compensator being simply connected in series.

(1.9.2) Metering Transformers.

Wound-type current transformers, such as are commonly used in supply metering, generally employ from 500 to 1 000 ampere-turns, and may therefore be compensated to have negligible errors if required. Whether the improvement in accuracy obtained justifies the extra cost must depend on individual circumstances. In a great number of cases Class AM (BS 81/1936) is quite good enough, and as this accuracy is often obtainable by normal design it follows that compensation will not usually be necessary. Moreover, metering transformers of the same type may in practice be required to work on a variety of burdens.

On systems of exceptionally high short-circuit capacity, however, it is essential in the interests of safety to keep the number of ampere-turns in wound-type current transformers to the lowest possible figure. The poor accuracy obtained consequent on the reduction of ampere-turns is a source of considerable difficulty in h.t. metering, and in such cases compensation should often provide a solution to the problem.

Regarding ring-type transformers, it is possible, using compensation in conjunction with Mumetal cores of normal size, to obtain errors within 2 min over the normal current range for a ratio of 100/5 amp. In view of this it seems that ring transformers should have a much wider scope in future.

(1.9.3) Bushing Transformers of Low Ratio.

Perhaps one of the most important uses of compensation is its application to the construction of ring transformers for h.v. metering. The cost of wound-type transformers for 22 kV and upwards is very high, and one such unit may occupy as much space as a small power transformer. Simple transformers of the ring type, fitted over the main transformer or alternator bushings, offer very great advantages in cost, safety and saving of space. In fact the possibility of their use is often the deciding factor as to whether h.v. metering may be employed.

The use of bushing transformers of normal design is limited for two principal reasons: (*a*) the comparatively small line currents experienced on h.v. systems, and (*b*) the large diameter of the bushings, resulting in the transformer cores having long magnetic paths and needing in consequence more magnetizing ampere-turns.

Increasing the core section of such transformers has little effect on the errors owing to the unfavourable shape of the magnetizing curve of the iron. Especially is this so when the outside diameter is increased, since the lines of force tend to crowd round the inside of the core owing to the shorter magnetic path.

This crowding is greater than is generally realized, and the author has made a mathematical investigation of this point and its effect on transformer errors. The mathematics is given in Appendix 5.2, and the results are expressed in graphical form in Figs. 4, 5 and 6. Fig. 4 shows the relative flux densities at different diameters for a given number of magnetizing ampere-turns. In calculations on ring-type cores it is generally assumed that the flux density is uniform, but from these curves it is seen

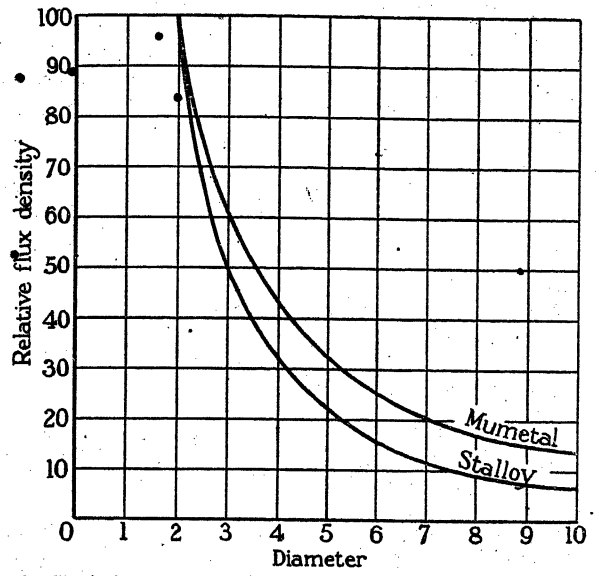


Fig. 4.—Variation of flux density with diameter for given magnetizing ampere-turns through core.

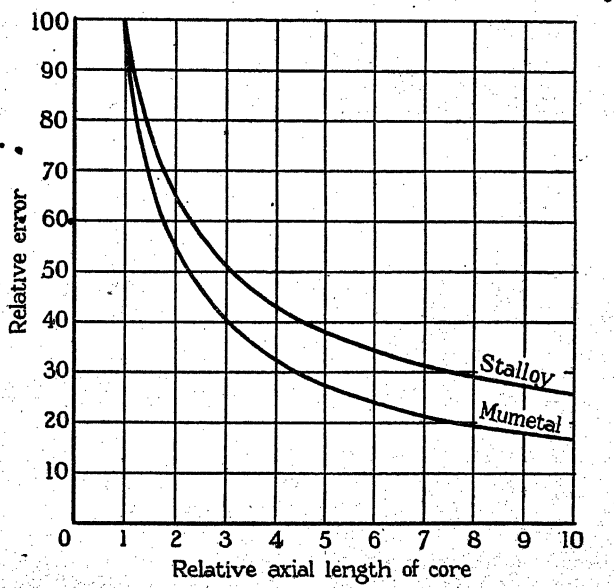


Fig. 5.—Variation of error with increase in axial length of core.

that at a diameter of 4 in, say, the density for Stalloy is only 32·5% of the value at diameter 2 in. Mumetal gives a more even distribution owing to its relatively straighter magnetization curve.

Figs. 5 and 6 give the variation in transformer error which may be expected when the axial length and outside diameter of the core are varied. In Fig. 6 the error is given in terms of the ratio of the outside to the inside diameters; thus, for a fixed inside diameter, the diameter ratio x is a measure of the outside diameter.

In terms of increase in weight the advantage obtained by undue increases in outside diameter are very small. For example, an increase of x from 1·1 to 10 gives a reduction in error of 100 down to 22 parts for a Stalloy core. The corresponding increase in core weight is in the ratio of 472 : 1.

The curves in Figs. 5 and 6 may be used in practice to estimate the approximate reduction in the error of a transformer for given increases in length and outside diameter.

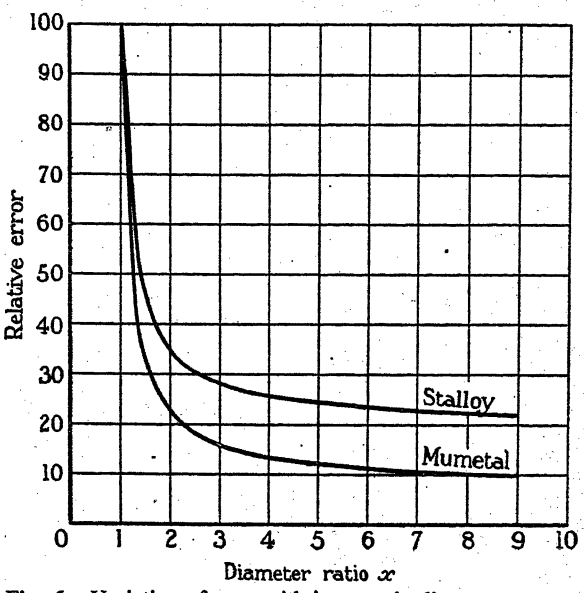


Fig. 6.—Variation of error with increase in diameter of core.

As an example, suppose a Mumetal transformer to have a core 10 cm long, 12 cm inside diameter and 18 cm outside diameter. The effect on the error will be estimated if the core length is increased to 15 cm and the outside diameter to 24 cm.

From Fig. 5 it is seen that increasing the axial length of the core from 10 to 15 cm (i.e. in the ratio 1 : 1·5) reduces the error in the ratio 100 : 72.

The diameter ratio x is increased from $18/12 = 1{\cdot}5$ to $24/12 = 2$. Referring to Fig. 6, the consequent reduction in error is in the ratio $44{\cdot}5 : 34$.

Taking the error for the smaller core as 100, we have:—

$$\text{Error for larger core} = 100 \times \frac{72}{100} \times \frac{34}{44{\cdot}5} = 55$$

The increases in core length and outside diameter have therefore caused a reduction in error in the ratio 100 : 55. It should be noted that to obtain this benefit the core has been increased to 3·6 times its former weight.

The effect of increased core section on the errors of transformers compensated by the author's method is much greater than with normal transformers, and may be reasoned out as follows.

If the natural error of the main current transformer is e_1 per cent, and that of the compensator e_2 per cent, the overall error of the whole transformer is given approximately by:—

$$\text{Total error} = e_2 \text{ per cent of } e_1 \text{ per cent} = \frac{e_1 e_2}{100} \text{ per cent.}$$

For the sake of simplicity the effect of increasing the axial length only will be considered.

Supposing the axial lengths of both cores to be increased in the ratio $1 : r$, the new values of the individual errors will be, referring to expression (8) in Appendix 5.2,

$$\text{New value of main error} = e_1 \times \left(\frac{1}{r}\right)^{\frac{1}{n}}$$

$$\text{New value of compensator error} = e_2 \times \left(\frac{1}{r}\right)^{\frac{1}{n}}$$

The new value of the overall error is the product of the individual errors divided by 100, i.e.

$$\text{New value of total error} = \frac{e_1 e_2}{100} \times \left(\frac{1}{r}\right)^{\frac{2}{n}}$$

The index $2/n$ is 1·2 for Stalloy and 1·6 for Mumetal.

The striking point about this expression is that the index $1/n$ has been doubled, which represents a very pronounced advantage for the compensated transformer. It has so far been considered almost useless in many cases to employ the whole of the space available for bushing transformers owing to the small gain in accuracy obtained. The value of $2/n$ for Mumetal is 1·6, however, and the provision of extra core weight is clearly well worth while when the accuracy improves with the 1·6th power of the weight.

The last expression is shown graphically in Fig. 7, for Mumetal

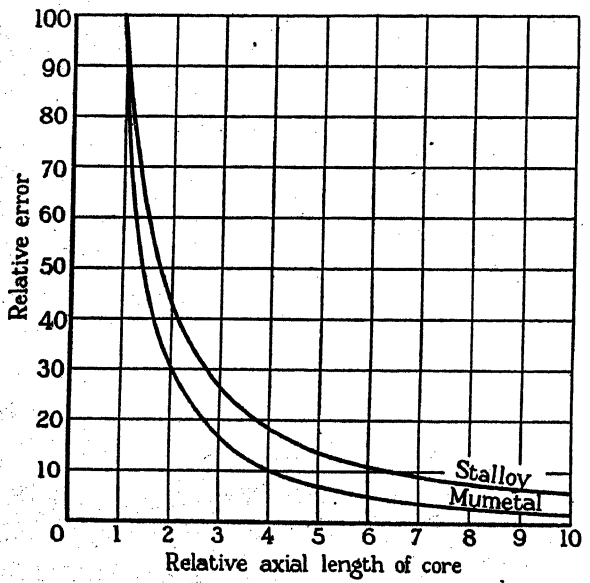


Fig. 7.—Reduction of error of compensated transformer with increase in axial length of core.

and Stalloy. It is seen that doubling the length of a Mumetal compensated transformer reduces the error to about one-third of its previous value. These curves should be compared with those in Fig. 5 for normal transformers.

The reduction in error for increase in diameter is naturally less, and is approximately given by the squares of expressions (11) and (12) in Appendix 5.2.

When the ratio between the permissible inside and outside diameters is uneconomically large, however, a fuller use may be made of the outside part by making the main and compensator cores of different diameters so as to fit one over the other as shown in Fig. 8.

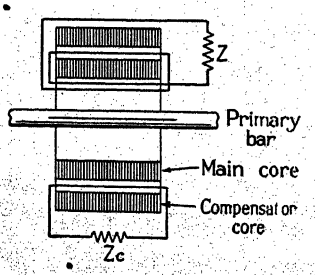


Fig. 8.—Use of cores of different diameters on low-ratio bushing transformers.

The diameter ratio x is by this means kept reasonably small in each case, while both cores may have the full available axial length. Such cores will almost invariably be of the Mumetal clock-spring type so that no difficulty arises regarding sizes of stamping tools.

Owing to war conditions and the consequent difficulty of obtaining experimental material the author has been compelled to curtail investigations on low-ratio bushing transformers. In Table 5, however, very good results are shown for a 50/5-amp transformer having a small core weight for such types, and from the foregoing notes and figures it appears that, using compensation and possibly some form of pre-magnetization, there is no reason why transformers of reasonable weight and having good metering accuracy should not be constructed for primary currents of 25 amp and even less.

(2) VOLTAGE-TRANSFORMER TESTING

Most methods of testing voltage transformers are absolute, employing a tapped high voltage resistor, the basic principle being shown in Fig. 9. In such methods the resistor is con-

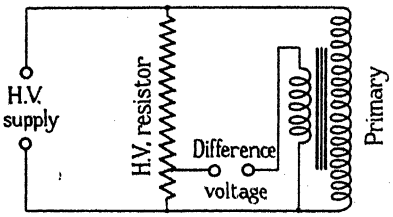


Fig. 9.—Principle of absolute methods of testing voltage transformers using a tapped h.v. resistor.

nected to the same high-voltage supply as the transformer under test. The secondary voltage of the transformer is opposed to a known fraction of the primary voltage, obtained from a tapping on the resistor. Finally the vector difference between these voltages is measured and resolved into components in phase and in quadrature with the primary voltage, and the ratio and phase-angle errors calculated therefrom.

While resistor methods are eminently suitable for laboratory work they suffer from several disadvantages from the point of view of the meter engineer, who is after all the man most concerned with voltage transformer errors.

High-voltage resistors of the electrostatically shielded type are bulky and expensive, and seldom have any use other than the one under discussion. In most test rooms only about half a dozen voltage transformers need to be tested in a year, and it is therefore not surprising that comparatively few undertakings are equipped for this purpose, although most of them are able to carry out tests on current transformers. Lesser disadvantages of resistors are the danger to the operator arising from the direct connection of the measuring apparatus to the h.v. supply and the large amount of power consumed on the higher voltages.

Relative methods of testing, i.e. by comparison with a standard transformer, do not seem to have found much favour up to the present. Very few methods have been suggested; possibly this is due to the supposed difficulty of designing multi-range standard transformers of the required precision. In fact a precision voltage transformer is probably less difficult to design than a shielded resistor having similar ratio and phase-angle characteristics. The resistor may have the advantage when a large number of different ratios are to be tested, but it should be remembered that in the majority of test rooms only two or three voltage transformer ratios are normally used. It is a simple matter to construct a standard transformer having a phase-angle error of 2 to 3 min, and even this error may be eliminated by means of a condenser connected across the secondary winding, since the transformer is always used on the same burden.

The relative method of testing about to be described was originally designed with the object of adapting the current trans-

former apparatus devised by Dr. A. H. M. Arnold[2] for testing voltage transformers, rendering the same equipment available for both purposes. This object has been satisfactorily achieved, but the method is not limited to this particular apparatus and may in fact be used with many existing a.c. potentiometers.

The set measures the difference in error between the standard and test transformers, with an accuracy and sensitivity comparable with those obtained when testing current transformers. The final accuracy will probably be rather less, however, because it is not possible at present to measure the error of the standard as accurately as that of a standard current transformer. Taking all factors into account, the readings obtained from the set should be within about 1% of their correct values. The errors of the standard must be determined by an absolute method, and it is improbable that the results obtained will be nearer to the correct figures than 0·02% in ratio and 0·5 min in phase angle.

The principle of relative methods is shown in Fig. 10. The

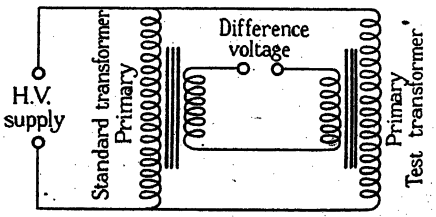


Fig. 10.—Principle of testing voltage transformers by comparison with a standard transformer.

primary windings of the test transformer and a standard having the same nominal ratio are connected in parallel to the same h.v. supply and the secondary voltages are opposed as shown. The vector difference of the secondary voltages is thus obtained, representing the difference in error between the two transformers, and this requires to be measured.

The method may be used without further complication to check an ordinary transformer against a standard or two similar transformers against each other. This is done by connecting a low-reading voltmeter so as to read the difference voltage. Generally the value of the difference voltage should not exceed 1·5 for a Class B transformer having a 110-volt secondary, although a large burden of low power factor may cause a reading of 2 volts. When similar transformers of the same make are being checked in this way the difference voltage should be almost unreadably small.

The high resistance of a.c. milliammeters sometimes enables them to be used for this test.

When actual ratio and phase-angle errors are to be determined the components of the difference voltage in phase and in quadrature with the main voltage require to be measured. In the present method this measurement is effected by an a.c. potentiometer consisting of a slide resistance and a mutual-inductance standard.

Fig. 11 shows the method of obtaining the necessary reference

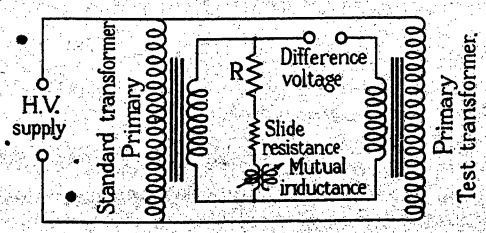


Fig. 11.—Method of obtaining in-phase and quadrature components of e.m.f. for potentiometer.

e.m.f.'s for the potentiometer. R is a non-inductive resistance having a value 2 000 or more times that of the slide resistance or mutual reactance, so that the current flowing in this part of the circuit is in phase with the standard secondary voltage within 2 min or less. In consequence the potential differences across the slide resistance and the mutual inductance are respectively in phase and in quadrature with the secondary voltage of the standard, i.e. in the correct phase positions for measuring the components of the difference voltage.

The difference voltage cannot be applied directly to the potentiometer, for two reasons; first, the secondary of the test transformer would thereby be short-circuited, and secondly the voltage, across the potentiometer is much smaller than the difference, which must consequently be stepped down to a suitable value for measurement. To overcome these difficulties a small transformer is used as shown in the complete diagram in Fig. 12. The

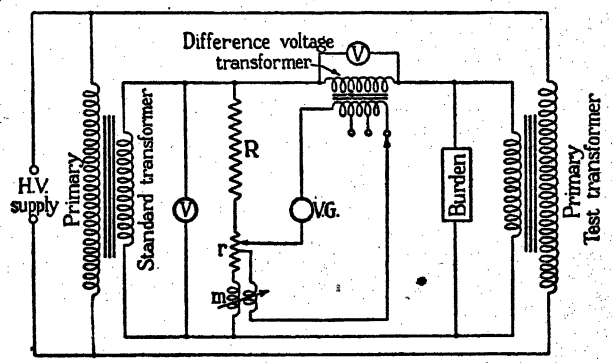


Fig. 12.—Complete diagram showing method of testing voltage transformers.

errors of this transformer are estimated to be less than 0·1% ratio and 2 min phase angle, and these have a negligible effect on the measurements made by the apparatus. Secondary tappings may be used if required to give extra ranges of measurement.

A small voltmeter, reading about 10 V full scale, is so connected as to read the difference voltage, and it serves to check the circuit connections, the ratio of the standard transformer, and the polarity. If these details are correct the voltmeter reading will not exceed 2 volts for transformers of normal accuracy. If the polarity of either transformer is reversed, approximately double the secondary voltage (about 220 volts) will appear across the difference voltmeter. If the nominal ratios of the standard and test transformers are not the same, a reading greatly in excess of 2 volts will be obtained.

In conducting a test, therefore, the difference voltmeter must be watched as the applied voltage is increased. It is soon obvious if an error has been made, and the supply may then be switched off and the mistake corrected.

When the potentiometer is balanced no current flows in the secondary of the difference-voltage transformer, and only a very small magnetizing current flows in the primary. The total current taken by this transformer and the difference voltmeter is less than 2 mA, representing a burden of about 0·2 VA on the test transformer. This has a negligible effect on the errors in the vast majority of cases.

In the particular adaptation of the method for use with the potentiometer of the Arnold current-transformer set, the resistance R may be 100 ohms, imposing a burden of 110 watts on the standard transformer. This is not excessive since a voltage transformer having very small errors must have extremely low resistance and leakage reactance. The set measures the difference in error between the standard and test transformers. If the

errors of the standard with its working burden connected are known, therefore, this burden has no effect on the accuracy of the method.

A voltmeter reading up to 125 volts is needed to indicate the secondary voltage of the standard. This imposes a small extra burden of about 5 VA.

The difference-voltage transformer is very small and, for the case under consideration, has turn ratios of 4 000, 2 000 and 400 to 1 obtained by secondary tappings. These give three ranges of measurement, viz. 2% and 100 min, 1% and 50 min, and 0·2% and 10 min.

The complete apparatus is fitted in a box, the terminal arrangement being such as to facilitate connection to the Arnold current-transformer set. The method of connection is shown in Fig. 13.

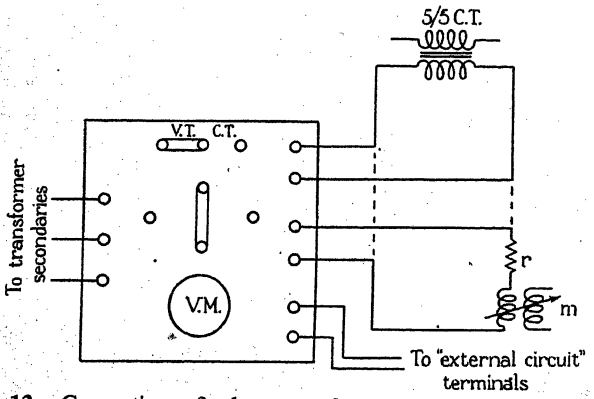


Fig. 13.—Connections of voltage-transformer set to the Arnold equipment.

One small alteration needs to be made to the Arnold set. Two leads connect the secondary of the 5/5-amp isolating transformer to the slide resistance and the primary of the mutual inductance. These leads require to be broken at one point and the four ends connected to two pairs of terminals provided on the voltage-transformer equipment. The Arnold set has two spare pairs of terminals which enable the potentiometer to be connected to an external circuit. One pair needs to be connected to the terminals marked "potentiometer" on the voltage-transformer set.

The change-over from current to voltage transformer testing is effected by changing a link, shown in Fig. 13 at the top of the panel, and by moving the rotary switch on the Arnold set to the "external circuit" position. Another link serves to change the testing range.

In a modification of the method the sensitivity is much increased and the burden on the standard reduced, by supplying the potentiometer elements through a step-down transformer. This arrangement is shown in Fig. 14, the primary of the new transformer being connected across the secondary of the standard. A suitable ratio for this transformer is 110/5·5 volts, and if R is made 2 ohms the burden on the standard is reduced to 15 watts plus the internal burden of the additional transformer. The current in the potentiometer elements would thereby be increased to 2·75 amp from 1·1 amp, with consequent increase in sensitivity.

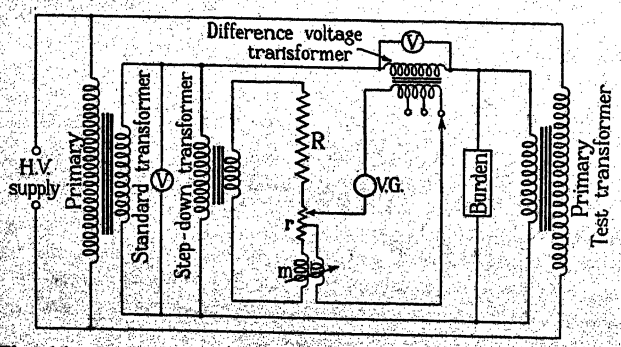


Fig. 14.—Voltage-transformer testing equipment with step-down transformer.

The accuracy of this transformer is only of secondary importance; for instance if it had an error of 1% the measurements made by the apparatus would be affected by 1%, so that a phase-angle reading of 20 min would have an error 0·2 min, which is negligible in practice. In consequence this transformer may be quite small; it is a simple matter so to design it that its errors are negligible, say 0·2% and 5 min, at its working burden.

(2.1) Theory of Method

Current in potentiometer elements $= V_s/R$
Voltage across $r = V_s r/R$ in phase with V_s
Voltage induced in secondary of $m = V_s \omega m/R$ in quadrature with V_s

At balance,

$$v_r/n = V_s r/R$$
$$v_x/n = V_s \omega m/R$$

Therefore difference in ratio error between standard and test transformers $= v_r/V_s = nr/R$

and difference in phase angle of standard and test transformers $= v_x/V_s = \omega mn/R$

(3) ERRORS OF THREE-PHASE VOLTAGE TRANSFORMERS

When watt-hour meters are to operate with current and voltage transformers it is theoretically preferable to carry out the meter calibration with the transformers in circuit, so that the errors of the transformers are automatically allowed for in the test. By this method an additional advantage is obtained in that the transformers are operating on their actual working burdens when the test is carried out, and the proper error values are therefore applied to the meter.

So far as current transformers are concerned little practical difficulty is encountered in doing this and it is, in fact, customary to include the current transformers in the meter-testing circuit. For various reasons, however, it is generally impracticable to calibrate meters with voltage transformers in circuit, and instead the usual plan is to make an allowance for the transformer errors. This involves (*a*) the accurate determination of the errors at the working burden of the transformer, and (*b*) the correct application of these errors in calibrating the meter.

Little difficulty is experienced in applying the errors correctly, but their accurate determination is more involved, especially in the case of 3-phase transformers, and this process is indifferently carried out at the present time. It is not generally realized that quite large errors in metering, amounting to 2–3% in some cases, may be incurred by using incorrect methods of estimating voltage-transformer errors.

The total error of a voltage transformer is the algebraic sum of a constant no-load error and a variable error due to the burden. The variable portion is merely the impedance voltage-drop in the transformer due to the flow of burden current, resolved into in-phase and quadrature components representing the ratio and phase-angle errors.

In accordance with B.S. 81/1936, makers of voltage transformers usually give the errors at zero burden and at full rated burden (non-inductive). The constant error is thus given directly, the difference between the two ratio errors is a measure of the

resistance of the transformer, and the difference between the two phase angles is a measure of the leakage reactance. Enough information is therefore available to enable the total error at any burden or power factor to be worked out, the process being very similar to the calculation of the voltage regulation of a power transformer.

The accuracy attained in the calculations depends mainly on the accuracy of the available test results and on the care taken in measuring the working burden and its power factor. A number of tests carried out by the author to check such calculations gave figures agreeing within 4% of the estimated values. The methods of testing used were the one described in Section 2 of this paper and the one due to Agnew and Silsbee.[9] Ordinary commercial instruments were used in measuring the burdens.

The problem of single-phase transformers has already been solved by mathematical and graphical means, and suitable references are given in the Bibliography. Probably the quickest is the graphical method due to Möllinger and Gewecke,[10] which is fully described in several English publications and notably in Hague's book on "Instrument Transformers."[1] Gewecke[13] also developed a diagram for 3-phase transformers which is, however, rather cumbersome to use and is not readily available to most engineers.

The remainder of the present paper is devoted to methods of estimating the errors of 3-phase star-star voltage transformers under any condition of burden from test results at unity power factor. The special object in view has been to provide a complete solution to the problem in such a way as to meet the practical needs of meter engineers who are too busy with other matters to make a specialized study of voltage-transformer theory.

The Möllinger and Gewecke (M. and G.) single-phase diagram is used in the solutions for 3-phase transformers, so that a knowledge of it is necessary to the understanding of the rest of the paper. Phase angles must be expressed in centiradians when using the diagram; minutes and centiradians are given side by side in the tables of results. The term "phase angle per cent" is used in the text instead of "centiradian." In the author's view this term is preferable as it is the quadrature equivalent of "ratio per cent."

(3.1) Three-Phase Transformers

It must first be remarked that accurate error figures on 3-phase transformers can only be obtained if a true 3-phase supply is used in the tests. Sometimes tests are carried out on each leg or phase in turn, using a single-phase supply. The results obtained in this way are certainly useful in that they give some idea of the errors and thus verify the correctness of design and construction. There is, however, no clear mathematical connection between such figures and the true errors.

Two methods of dealing with 3-phase transformers are given below.

The test certificates supplied by manufacturers usually give the errors of each phase to neutral at zero burden and full rated burden (non-inductive), a total of six tests. Using these figures the first method shows how to work out the errors for any burden or combination of burdens, balanced or unbalanced. This method is very useful in that it may be applied to the many transformers already in stock or in service without further tests being needed, and it may also be applied to a set of three single-phase voltage transformers connected to form a 3-phase star-star bank, provided the h.v. neutral is earthed.

In 3-phase 3-leg transformers the displacement of the neutral point due to unbalanced burdens is very small and has no appreciable effect on the errors.

The process is, however, rather laborious, and the author has devised an easier method in which the work is reduced to a number of simple applications of the single-phase M. and G. diagram. This, the second method to be described, employs the results of a number of special tests on non-inductive burdens.

Method 1.—*Determination of the Working Errors of a* 3*-phase Voltage Transformer from the Normal Phase-Neutral Test Results.*

The procedure is in two distinct parts:—

(*a*) From the known values of the phase-phase burdens and their power factors the errors of each phase to neutral under actual working conditions are estimated.

(*b*) Using these phase-neutral figures the phase-phase errors are then calculated from the following formulae which have been given by Hague but which are deduced below in a simpler manner.

In Fig. 15(*a*) the phase-phase voltage V_{AB} is the vector difference between the phase-neutral voltages V_A and V_B. It is required to estimate the effect on V_{AB} of small errors in phase and in quadrature with V_A and V_B.

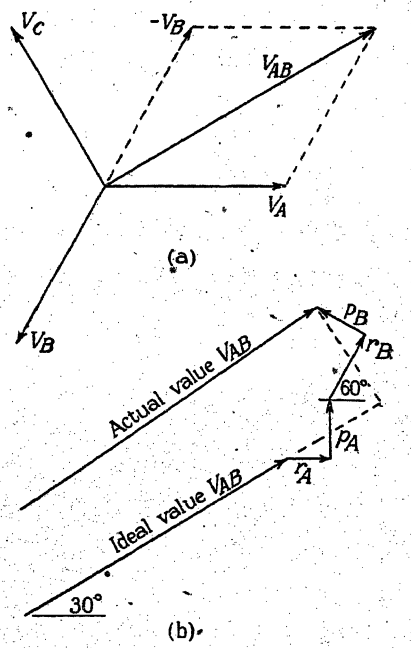


Fig. 15.—Deduction of phase-phase errors from phase-neutral errors.

The important part of the vector diagram is shown in Fig. 15(*b*) in which r_A, p_A, r_B and p_B are the percentage ratio and phase-angle errors of V_A and V_B respectively. These are all given positive values for convenience. In constructing Fig. 15(*b*) it should be remembered that r_A and p_A are respectively in phase and in leading quadrature with V_A, and that similarly r_B and p_B are in phase and in leading quadrature with V_B. The dotted lines in the diagram represent the resultant in-phase and quadrature errors of V_{AB}, and an examination shows that

$$\text{In-phase error} = 0{\cdot}866(r_A + r_B) + 0{\cdot}5(p_A - p_B)$$
$$\text{Quadrature error} = 0{\cdot}866(p_A + p_B) + 0{\cdot}5(r_B - r_A)$$

These values require to be divided by $\sqrt{3}$ to obtain the percentage ratio and phase-angle errors, since r_A, r_B, etc., are percentages of the phase-neutral voltages, whereas the phase-phase voltage is $\sqrt{3}$ times larger.

The final expressions are:—

$$\text{Ratio error of } V_{AB} = 0{\cdot}5(r_A + r_B) + 0{\cdot}289(p_A - p_B) \quad (1)$$

$$\text{Phase angle of } V_{AB} = 0{\cdot}5(p_A + p_B) + 0{\cdot}289(r_B - r_A) \quad (2)$$

It should be noted that in these formulae A is the leading phase.

Example of Method.

Table 6 gives the phase-neutral errors of a 3-phase Class B transformer, the loading being phase-neutral. The phase-phase errors will be deduced for the following burden conditions:—

Phase AB .. .. 30 VA; current lagging 20°
Phase BC .. .. 35 VA; current lagging 45°
Phase CA .. .. 25 VA; current lagging 75°

Table 6

ERRORS OF 3-PHASE VOLTAGE TRANSFORMER, PHASE-NEUTRAL, USED IN EXAMPLE ON METHOD 1

Burden (non-inductive)	Phase A–N			Phase B–N			Phase C–N		
	Ratio error	Phase angle		Ratio error	Phase angle		Ratio error	Phase angle	
VA	%	min	%	%	min	%	%	min	%
0	+ 0·7	+ 25	+ 0·725	+ 0·8	+ 10	+ 0·291	+ 0·7	+ 26	+ 0·755
50	− 0·6	+ 20	+ 0·580	− 0·5	+ 5	+ 0·145	− 0·6	+ 21	+ 0·610

Fig. 16 gives the complete vector diagram, drawn to scale, the dotted lines representing the reversed current vectors. The total current in each leg is the vector difference between two of the currents shown, i.e.

Current in phase A $= I'_{AB} - I'_{CA}$
Current in phase B $= I'_{BC} - I'_{AB}$
Current in phase C $= I'_{CA} - I'_{BC}$

The obvious procedure is first to work out vectorially the total current in each leg and its phase position, and then to use the M. and G. diagram to determine the errors of each leg in turn.

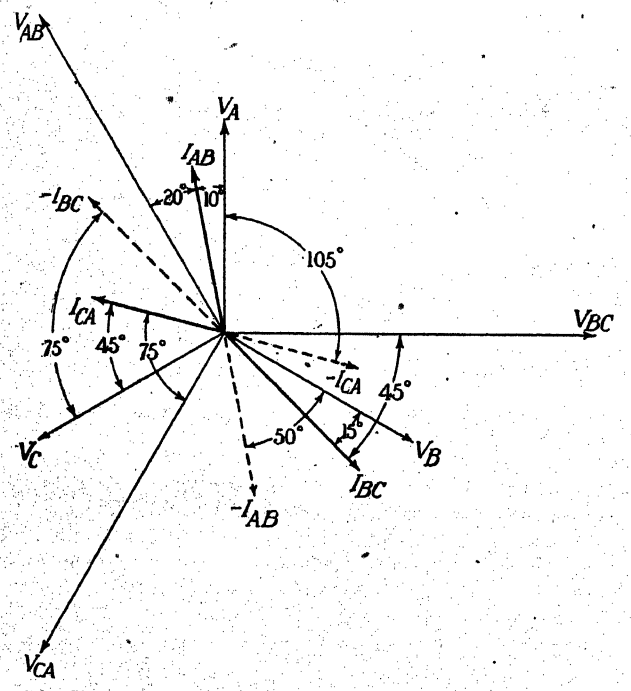


Fig. 16.—Vector diagram of 3-phase voltage transformer with unbalanced burden (Example 2).

This, however, involves three rather tedious vector calculations, and a quicker way is to use the M. and G. diagram twice for each leg, once for each component of current, and to sum the effects to obtain the total change in error for that leg.

It must be remembered here that the figures given in Table 6 relate to phase-neutral burdens and that accordingly the phase-phase working burdens require to be divided by $\sqrt{3}$ to obtain the corresponding phase-neutral values.

Further, in applying the M. and G. diagram the angle between the current vector and the corresponding *phase-neutral* voltage must be used. If ϕ is the angle between current and phase-phase voltage, the angle between current and phase-neutral voltage will be either $(\phi - 30)$ or $(\phi + 30)$, according to whether or not the current vector has to be reversed.

In a normal transformer the three legs will be of identical design, so that to a sufficiently close approximation their resistances and leakage reactance will be equal. In consequence the changes of error for a given burden at unity power factor will be the same for each leg, and only one M. and G. diagram need be drawn for the whole transformer.

In the present case, for instance, for 50 VA non-inductive, the error-changes, from Table 6, are − 1·3% ratio and − 5 min (− 0·145%) phase angle. The diagram for this transformer is given in Fig. 17, in which six different characteristics have been

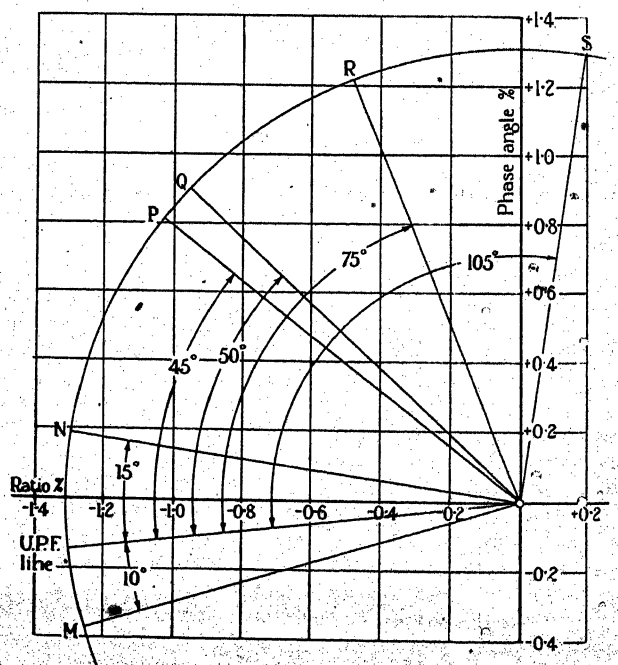


Fig. 17.—Möllinger and Gewecke diagram for 3-phase transformer (Method 1).

drawn for the various phase displacements between current and phase-neutral voltages shown in Fig. 16. The points M, N, P, Q, R and S give the error changes for 50 VA phase-neutral burden for the angles indicated.

The phase-neutral errors at working burden of the three legs are obtained as follows.

Phase A.

From Fig. 16 it is seen that the burden currents in this phase are I_{AB} and $-I_{CA}$. These correspond to the following phase-neutral burdens:—

$30/\sqrt{3}$ or 17·3 VA; current leading V_A by 10°
$25/\sqrt{3}$ or 14·4 VA; current lagging V_A by 105°

The points M and S in Fig. 17 give the changes in error for 50 VA at these angles; these are − 1·25% ratio and − 0·37% phase angle in the first case, and + 0·19% ratio and + 1·29% phase angle in the second case.

For a given power factor the change in error of a voltage transformer is proportional to the burden, so that we have

Ratio-error change due to I_{AB}
$= -1{\cdot}25 \times 17{\cdot}3/50 = -0{\cdot}435\%$

Phase-angle change due to I_{AB}
$= -0{\cdot}37 \times 17{\cdot}3/50 = -0{\cdot}128\%$

and

Ratio-error change due to $-I_{CA}$
$= +0{\cdot}19 \times 14{\cdot}4/50 = +0{\cdot}055\%$

Phase-angle change due to $-I_{CA}$
$= +1{\cdot}29 \times 14{\cdot}4/50 = +0{\cdot}373\%$

The total errors of this phase are obtained by summing the zero burden errors and the above error changes, i.e.

Working ratio error of phase A
$= +0{\cdot}7 - 0{\cdot}435 + 0{\cdot}055 = +0{\cdot}320\%$

Working phase angle of phase A
$= +0{\cdot}725 - 0{\cdot}128 + 0{\cdot}373 = +0{\cdot}970\%$

Phase B.

Referring to Fig. 16, the burden currents are I_{BC} and $-I_{AB}$, corresponding to

$35/\sqrt{3}$ or 20·2 VA; current lagging V_B by 15°
and $30/\sqrt{3}$ or 17·3 VA; current lagging V_B by 50°

From the points N and Q in Fig. 17 we have:—

Ratio-error change due to I_{BC}
$= -1{\cdot}3 \times 20{\cdot}2/50 = -0{\cdot}525\%$

Phase-angle change due to I_{BC}
$= +0{\cdot}19 \times 20{\cdot}2/50 = +0{\cdot}077\%$

and

Ratio-error change due to $-I_{AB}$
$= -0{\cdot}95 \times 17{\cdot}3/50 = -0{\cdot}329\%$

Phase-angle change due to $-I_{AB}$
$= +0{\cdot}89 \times 17{\cdot}3/50 = +0{\cdot}310\%$

The total errors of phase B are found, as before, by summing the zero burden errors and the error changes worked out above, i.e.

Working ratio error of phase B
$= +0{\cdot}8 - 0{\cdot}525 - 0{\cdot}329 = -0{\cdot}053\%$

Working phase angle of phase B
$= +0{\cdot}291 + 0{\cdot}077 + 0{\cdot}310 = +0{\cdot}678\%$

Phase C.

The burden currents (Fig. 16) are I_{CA} and $-I_{BC}$, corresponding to

$25/\sqrt{3}$ or 14·4 VA, current lagging V_C by 45°
and $35/\sqrt{3}$ or 20·2 VA, current lagging V_C by 75°

From the points P and R in Fig. 17 we have:—

Ratio-error change due to I_{CA}
$= -1{\cdot}03 \times 14{\cdot}4/50 = -0{\cdot}295\%$

Phase-angle change due to I_{CA}
$= +0{\cdot}81 \times 14{\cdot}4/50 = +0{\cdot}233\%$

and

Ratio-error change due to $-I_{BC}$
$= -0{\cdot}48 \times 20{\cdot}2/50 = -0{\cdot}195\%$

Phase-angle change due to $-I_{BC}$
$= +1{\cdot}22 \times 20{\cdot}2/50 = +0{\cdot}492\%$

Summing, the total errors for phase C are:—

Working ratio error of phase C
$= +0{\cdot}7 - 0{\cdot}295 - 0{\cdot}195 = +0{\cdot}210\%$

Working phase angle of phase C
$= +0{\cdot}755 + 0{\cdot}233 + 0{\cdot}492 = +1{\cdot}480\%$

Having now ascertained the working phase-neutral errors for each leg of the transformer, the phase-phase errors are worked out by substituting the phase-neutral errors in expressions (1) and (2), remembering that in these formulae A represents the leading and B the lagging phase.

We have:—

Ratio error of phase AB
$= 0{\cdot}5(0{\cdot}320 - 0{\cdot}053) + 0{\cdot}289(0{\cdot}970 - 0{\cdot}678) = +0{\cdot}22\%$

Phase angle of phase AB
$= 0{\cdot}5(0{\cdot}970 + 0{\cdot}678) + 0{\cdot}289(-0{\cdot}053 - 0{\cdot}320) = +0{\cdot}716\%$
$= +25$ min

Ratio error of phase BC
$= 0{\cdot}5(-0{\cdot}053 + 0{\cdot}210) + 0{\cdot}289(0{\cdot}678 - 1{\cdot}480) = -0{\cdot}15\%$

Phase angle of phase BC
$= 0{\cdot}5(0{\cdot}678 + 1{\cdot}480) + 0{\cdot}289(0{\cdot}210 + 0{\cdot}053) = +1{\cdot}155\%$
$= +40$ min

Ratio error of phase CA
$= 0{\cdot}5(0{\cdot}210 + 0{\cdot}320) + 0{\cdot}289(1{\cdot}480 - 0{\cdot}970) = +0{\cdot}413\%$

Phase angle of phase CA
$= 0{\cdot}5(1{\cdot}480 + 0{\cdot}970) + 0{\cdot}289(0{\cdot}320 - 0{\cdot}210) = +1{\cdot}26\%$
$= +43$ min

Method 2.—Simple Method of Determining the Working Errors of a 3-phase Voltage Transformer, using Special Test Results.

It is hoped that the following method will be found easier in principle and operation than the one already described, inasmuch as no vector analysis is needed and no 3-phase calculations are involved. Lest the fact that "special" tests are required should militate against the general use of the method, it should at once be explained that these are merely ordinary ratio and phase-angle tests carried out with normal apparatus and burdens, the only difference being in the connection of the burden. There is no reason, in fact, why manufacturers should not furnish, when requested, test results such as are used in this method instead of the usual phase-neutral figures.

The principle of the method is as follows.

Fig. 18 shows the connections of a star-star transformer with a 3-phase burden. Phase AB comprises the two legs A and B,

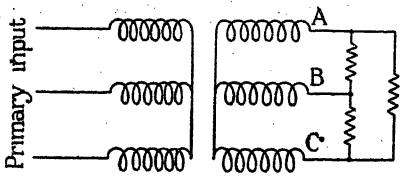


Fig. 18.—Star-star transformer with 3-phase burden.

and it is clear that a burden on any one of the three phases AB, BC or CA causes current to flow in leg A, leg B, or both. Consequently the errors of phase AB are affected not only by its own burden but also by the burdens on the other two phases; in short, a burden on one phase affects the errors of all three phases.

In order to have complete knowledge of the transformer performance it is therefore necessary to determine how much the errors of each phase vary when the other phases are loaded. This may be accomplished by carrying out four ratio and phase-angle tests on each phase, (*a*) with zero burden on all three phases, (*b*) with full rated burden on the particular phase in question, the other phases being unloaded, (*c*) and (*d*) with full rated burden on each other phase in turn, the remaining phases again being unloaded.

The total number of tests required is thus 12, compared with the customary 6 phase-neutral tests. The increase in the number of tests is no real disadvantage, however, and should not normally necessitate much extra time being spent in testing, since the same burden is used throughout and the changes in connections are very simple.

The complete list of tests required is shown in Table 7. It

Table 7

LIST OF RATIO AND PHASE-ANGLE TESTS NEEDED IN METHOD 2

Test No.	Tests on Phase AB with	Tests on Phase BC with	Tests on Phase CA with
1	Zero burden	Zero burden	Zero burden
2	Full non-inductive burden on AB only	Full non-inductive burden on BC only	Full non-inductive burden on CA only
3	Full non-inductive burden on BC only	Full non-inductive burden on CA only	Full non-inductive burden on AB only
4	Full non-inductive burden on CA only	Full non-inductive burden on AB only	Full non-inductive burden on BC only

should be noted that when the transformer is to be loaded on two phases only, as is often the case, the number of tests needed is reduced to 6, and the labour in the calculations reduced by rather more than half.

It will be seen that, by means of these special tests, three unity-power-factor characteristics are obtained for each phase. Taking any one phase, the changes in error of that phase due to the three burdens may be determined separately by means of the M. and G. diagram. The total error of that phase is then found by adding the zero-burden error to the sum of the three error changes.

Example of Method.

The working of the method will be amply illustrated by carrying out the calculations on one phase of a transformer actually constructed at the author's works and tested to verify the method.

Table 8 gives the four sets of ratio and phase-angle errors for

Table 8

TEST RESULTS ON PHASE AB of 3-PHASE VOLTAGE TRANSFORMER

(*These figures are used in the Example on Method* 2)

Burden (non-inductive)	Test results on Phase AB		
	Ratio error	Phase angle	
0	% −0·053	min +23·6	% +0·684
50 VA on AB only	−0·760	+17·0	+0·493
50 VA on BC only	−0·141	+11·7	+0·339
50 VA on CA only	−0·310	+32·0	+0·929

phase AB obtained from tests in accordance with Table 7. The unbalanced loading was as follows:—

Phase AB	.. ..	22·5 VA, non-inductive
Phase BC	.. ..	21 VA, current lagging 75°
Phase CA	.. ..	16·5 VA, current lagging 22°

The ratio and phase-angle errors of phase AB under these conditions are computed as follows.

Effect of Burden on Phase AB.

From Table 8 the change in ratio error for 50 VA on phase AB is $-0{\cdot}760 + 0{\cdot}053 = -0{\cdot}707\%$, and the change in phase angle is $(0{\cdot}493 - 0{\cdot}684) = -0{\cdot}191\%$.

Since the burden on this phase is non-inductive the error changes may be worked out by direct proportion, i.e.

Change in ratio error $= -0{\cdot}707 \times 22{\cdot}5/50 = -0{\cdot}318\%$
Change in phase angle $= -0{\cdot}191 \times 22{\cdot}5/50 = -0{\cdot}086\%$

Effect of Burden on Phase BC.

At 50 VA (non-inductive) we have:—

Change of ratio error $= -0{\cdot}141 + 0{\cdot}053 = -0{\cdot}088\%$
Change of phase angle $= +0{\cdot}339 - 0{\cdot}684 = -0{\cdot}345\%$

The M. and G. diagram is shown in Fig. 19(*b*). From it the error-changes for 50 VA on Phase BC, current lagging 22°, are $-0{\cdot}212\%$ ratio and $-0{\cdot}285\%$ phase angle.

For 21 VA, therefore, the error changes are:—

Change of ratio error $-0{\cdot}212 \times 21/50 = -0{\cdot}089\%$
Change of phase angle $-0{\cdot}285 \times 21/50 = -0{\cdot}120\%$

Effect of Burden on Phase CA.

At 50 VA (non-inductive) we have:—

Change of ratio error $= -0{\cdot}310 + 0{\cdot}053 = -0{\cdot}257\%$
Change of phase angle $= +0{\cdot}929 - 0{\cdot}684 = +0{\cdot}245\%$

The M. and G. diagram is given in Fig. 19(*a*). From this the changes in ratio and phase angle for 50 VA, current lagging 75°, are $+0{\cdot}17$ and $+0{\cdot}314\%$ respectively, and the figures for 16·5 VA at this power factor are therefore

Change of ratio error $= +0{\cdot}17 \times 16{\cdot}5/50 = +0{\cdot}056\%$
Change of phase angle $= +0{\cdot}314 \times 16{\cdot}5/50 = +0{\cdot}104\%$

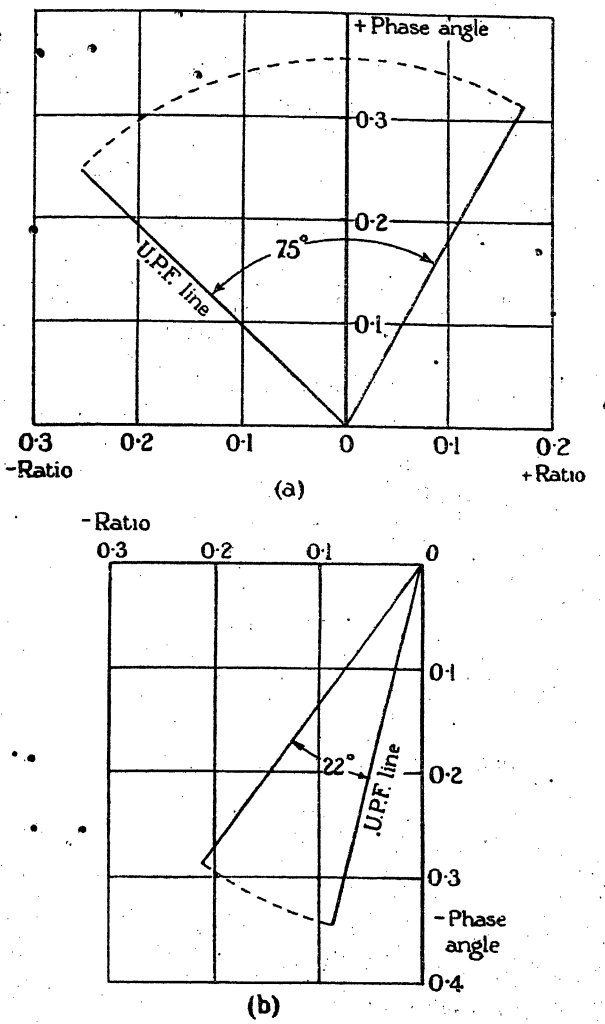


Fig. 19.—Möllinger and Gewecke diagrams.

(*a*) Errors due to burden on phase CA.
(*b*) Errors due to burden on phase BC.

The total working errors of phase AB are the sums of the zero-burden errors and the three changes worked out above, i.e.

Working ratio error of phase AB
$= -0{\cdot}053 - 0{\cdot}318 + 0{\cdot}056 - 0{\cdot}089 = -0{\cdot}40\%$

Working phase angle of phase AB
$= +0{\cdot}684 - 0{\cdot}086 + 0{\cdot}104 - 0{\cdot}120 = +0{\cdot}582\%$
$= +20$ min

The actual test figures obtained were $-0{\cdot}394\%$ and $+20{\cdot}3$ min.

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(5) APPENDICES

(5.1) Theory of Current-Transformer Compensator

Symbols.

I_1 = primary current.
I_2 = secondary current.
I_3 = current in compensator winding.
T_1, T_A, T_B, T_C = numbers of turns in primary and windings A, B, C.
E_2 = total secondary e.m.f.
E_A, E_B, E_C = induced e.m.f.'s in windings A, B, C.
$R + jX$ = total impedance of secondary circuit, comprising external burden, leads, and windings A and B.
$r + jx$ = total impedance of compensating circuit, comprising compensating burden and winding C.

Neglecting magnetization losses, I_2 and I_C are in phase with each other and in phase opposition to I_1.

For the main core $\quad I_1T_1 + I_2T_A = 0$

Therefore $\quad I_2 = -\dfrac{I_1T_1}{T_A}$

For the compensator core

$$I_1T_1 + I_2T_B + I_CT_C = 0$$

Therefore
$$I_C = \frac{-(I_1T_1 + I_2T_B)}{T_C} = \frac{-(-I_2T_A + I_2T_B)}{T_C} = \frac{I_2(T_A - T_B)}{T_C}$$

Now
$$E_2' = I_2(R + jX) = E_A' + E_B'$$
$$E_C' = I_C(r + jx)$$

Therefore
$$E_B' = E_C' \times \frac{T_B}{T_C} = \frac{I_CT_B(r + jx)}{T_C}$$

For complete compensation the flux in the main core is zero, hence

$$E_A' = 0$$

Therefore $E'_B = E'_2$

i.e. $$\frac{I_C T_B(r+jx)}{T_C} = I_2(R+jX)$$

Therefore $$r+jx = \frac{I_2 T_C}{I_C T_B}(R+jX)$$

Substituting for I_C this reduces to

$$r+jx = \frac{T_C^2}{T_B(T_A - T_B)}(R+jX)$$

This expression shows that the value of the compensating burden is independent of current and frequency, and that its power factor is the same as that of the total secondary burden.

The volt-amperes wasted in the compensating circuit may be arrived at as follows:—

$$\frac{\text{VA in compensating circuit}}{\text{VA in secondary circuit}} = \frac{I_C^2(r+jx)}{I_2^2(R+jX)}$$

$$= \frac{I_C^2}{I_2^2(R+jX)} \times \frac{I_2 T_C(R+jX)}{I_C T_B}$$

$$= \frac{I_C T_C}{I_2 T_B}$$

$$= \frac{\text{Ampere-turns in winding C}}{\text{Ampere-turns in winding B}}$$

(5.2) Performance of Bushing-Type Current Transformers

Examination of the performance curves of Stalloy and Mumetal, plotted on a logarithmic basis, gave the following approximate laws for flux densities up to about 4 000 gauss sinusoidal 50-c/s magnetization.

For Stalloy—$B \propto (\text{ampere-turns per cm})^{\frac{5}{9}}$ . . . (3)

For Mumetal—$B \propto (\text{ampere-turns per cm})^{\frac{5}{4}}$ . . . (4)

In these expressions the ampere-turns per cm include both the pure magnetizing and iron-loss components.

Taking the general expression

$$B = K \times (\text{ampere-turns per cm})^n \quad . . . . (5)$$

we have, for a given number of magnetizing ampere-turns A through the core,

$$\text{Ampere-turns per cm at radius } r = \frac{A}{2\pi r}$$

The flux density B_r at that radius is, from (5),

$$B_r = K\left(\frac{A}{2\pi r}\right)^n \quad . . . . . (6)$$

or, for a given core,

$$B_r \propto r^{-n} \quad . . . . . (7)$$

The curves in Fig. 4 were plotted from this expression. B_r was given a nominal value of 100 for $r = 1$, and n was given its appropriate values for Stalloy and Mumetal.

Next consider a transformer of fixed inside and outside diameters but of variable length l cm. For a given total flux Φ the flux density is inversely proportional to the axial length, i.e.

$$B \propto \frac{1}{l}$$

Transposing (5) we have

$$\text{Ampere-turns per cm} \propto B^{\frac{1}{n}}$$

Therefore in this case

$$\text{Ampere-turns per cm} \propto l^{-\frac{1}{n}}$$

As the core diameters are fixed, the length of the magnetic p is also fixed,

$$\text{Total magnetizing ampere-turns} \propto l^{-\frac{1}{n}} \quad . .$$

The total number of magnetizing ampere-turns represents t overall error of the transformer (i.e. the vector sum of the rat and phase-angle errors). In effect, therefore, this expressi gives the relation between transformer error and axial length o core when the core diameters remain constant. Curves are given in Fig. 5 for Stalloy and Mumetal. The error was given a nominal value of 100 for a core length of unity.

A formula giving the relation between the error and outside diameter of the core may be deduced as follows. Consider a core of length l centimetres, inside radius R and outside radius xR. Let A be the total magnetizing ampere-turns for this core. Then, from (5), the flux density at radius r cm is given by

$$B_r = K\left(\frac{A}{2\pi r}\right)^n$$

The total flux Φ in the core is given by

$$\Phi = l\int_R^{xR} B_r \, . \, dr = \frac{lKA^n}{2^n \pi^n}\int_R^{xR} r^{-n} \, . \, dr$$

or, for a core of given material, axial length and inside radius,

$$\Phi \propto A^n\left(\frac{x^{n-1}-1}{x^{n-1}}\right) \quad . . . . . (9)$$

This expression may be transposed to give A in terms of Φ and x.

$$A \propto \Phi^{\frac{1}{n}}\left(\frac{x^{n-1}}{x^{n-1}-1}\right)^{\frac{1}{n}}$$

and, for a given value of total flux,

$$A \propto \frac{x^{(n-1)/n}}{(x^{n-1}-1)^{1/n}} \quad . . . . . (10)$$

Since A represents the transformer error, expression (10) gives in effect the relation between the error and the ratio x of the outside to inside radius. For Stalloy ($n = 5/3$)

$$A \propto \frac{x^{0\cdot4}}{(x^{0\cdot67}-1)^{0\cdot6}} \quad . . . . . (11)$$

For Mumetal ($n = 5/4$)

$$A \propto \frac{x^{0\cdot2}}{(x^{0\cdot25}-1)^{0\cdot8}} \quad . . . . . (12)$$

The curves in Fig. 6 are drawn from these expressions. A number of values of x were taken and the relative values of A worked out. The error for $x = 1\cdot1$ was given a value of 100 and the others were adjusted in the same proportion.

(5.3) Theory of Voltage-Transformer Testing Equipment

Symbols.

V_t = secondary voltage of test transformer.
V_s = secondary voltage of standard transformer.
V = primary voltage of test and standard transformers.
v_r = component of difference voltage in phase with V_s.
v_x = component of difference voltage in quadrature with V_s.
k = nominal ratio, primary to secondary, of test and standard transformers.

K_t = (true ratio)/(nominal ratio) of test transformer.
K_s = (true ratio)/(nominal ratio) of standard transformer.
α = phase-angle error of standard transformer.
β = phase-angle error of test transformer.
$\omega = 2\pi f$
m = variable mutual inductance.
r = slide resistance.
R = fixed non-inductive resistance connected to potentiometer elements.
n = ratio of difference voltage transformer, primary to secondary.

Vector quantities indicated thus: V_t', V_s', etc.

The potentiometer theory in Section 2 gives the errors to the first order of accuracy only. A more rigorous treatment is given below in which the second powers of the test-transformer errors are taken into account. The approximations used are $\sin\alpha = \alpha$, $\cos\alpha = 1$, $\sin\beta = \beta$, $\cos\beta = 1 - \frac{1}{2}\beta^2$. Third and higher powers of nr/R and $\omega mn/R$ are ignored. K_s is very nearly unity, and the second power of its difference from unity is negligible.

$$V_s' = V'(\cos\alpha + j\sin\alpha)/kK_s$$
$$V_t' = V'(\cos\beta + j\sin\beta)/kK_t$$

Therefore
$$\begin{aligned} V_t'/V_s' &= K_s(\cos\beta + j\sin\beta)/K_t(\cos\alpha + j\sin\alpha) \\ &= K_s(1 - \tfrac{1}{2}\beta^2 + j\beta)/K_t(1 + j\alpha) \\ &= (1 - \tfrac{1}{2}\beta^2 + j\beta)(1 - j\alpha)K_s/K_t \\ &= (1 - \tfrac{1}{2}\beta^2 + j\beta - j\alpha)K_s/K_t \quad . \quad . \quad . \quad (13) \end{aligned}$$

Current in R $= V_s'/R$
Potentiometer voltage $= (r - j\omega m)V_s'/R$.

At balance,

$$(V_s' - V_t')/n = (r - j\omega m)V_s'/R$$
$$\begin{aligned} (r - j\omega m)n/R &= 1 - V_t'/V_s' \\ &= 1 - (1 - \tfrac{1}{2}\beta^2 + j\beta - j\alpha)K_s/K_t \quad \text{[from (13)]} \end{aligned}$$

Equating components,

$$rn/R = 1 - (K_s - \tfrac{1}{2}\beta^2)/K_t \quad . \quad . \quad . \quad . \quad . \quad (14)$$
$$\omega mn/R = (\beta - \alpha)K_s/K_t = (\beta - \alpha)/K_t \quad . \quad . \quad . \quad (15)$$

From (14),

$$1 - nr/R = (K_s - \tfrac{1}{2}\beta^2)/K_t$$

or
$$\begin{aligned} K_t &= (K_s - \tfrac{1}{2}\beta^2)(1 + nr/R + n^2r^2/R^2) \\ &= K_s + nr/R + n^2r^2/R^2 - \tfrac{1}{2}\beta^2 \end{aligned}$$

From (15)

$$\begin{aligned} \beta - \alpha &= K_t \times \omega mn/R \\ &= (K_s + nr/R + n^2r^2/R^2 - \tfrac{1}{2}\beta^2)\omega mn/R \end{aligned}$$

Therefore
$$\beta - \alpha = \omega mn/R + \omega mn^2r/R^2 \text{ radian} \quad . \quad . \quad (16)$$

$$K_t - K_s = nr/R + n^2r^2/R^2 - \tfrac{1}{2}\beta^2$$
$$\beta = \omega mn/R + \omega mn^2r/R^2$$

Therefore
$$K_t - K_s = nr/R + n^2r^2/R^2 - \omega^2m^2n^2/2R^2 \quad . \quad (17)$$

Since the graduation of the scales gives

$$K_t - K_s = nr/R$$
$$\beta - \alpha = \omega mn/R$$

The error of the ratio scale, from (17), is

$$n^2r^2/R^2 - \omega^2m^2n^2/2R^2$$

and the error of the phase-angle scale, from (16), is

$$\omega mn^2r/R^2$$

The maximum range of measurement of the apparatus is 2% in ratio and 100 minutes phase angle, i.e.

$$K_t - K_s = 0{\cdot}02 \qquad \beta - \alpha = 0{\cdot}029 \text{ radian.}$$

Therefore the maximum values of the scale errors work out at 0·04% ratio and 2 min phase angle. Most transformers have errors within 1% and 30 min, and the corrections are nearly always negligible in consequence, since they are proportional to the squares of the test-transformer errors.

DISCUSSION BEFORE THE MEASUREMENTS SECTION, 19TH NOVEMBER, 1943

Dr. A. H. M. Arnold: The author has developed an exceedingly ingenious piece of apparatus in his compensated transformer, and the figures given in Tables 1 to 5 show that the performance of this type of transformer is very good indeed. The explanation of the operation of his compensator is, however, less satisfactory. In the first place he confuses the issue by applying his compensator to an "ideal" transformer which would not require compensation, and in the second place he stresses the point that the flux in the main core is reduced to zero. Now if the flux in the main core is reduced to zero, this core and its associated windings may be eliminated and we obtain a simple transformer with primary, secondary and tertiary windings. By a suitable adjustment of the burden on the tertiary, the secondary current may be brought into phase with the primary current and equal to a convenient fraction of it. In other words, this transformer would have zero ratio error and zero phase angle at one load current, burden and frequency, exactly as Mr. Hobson's transformer has. Yet the general performance of such a transformer would be poor; it appears that the main core of Mr. Hobson's transformer must play a very important part in the operation of the transformer and it must therefore carry flux even though the amount is small. In point of fact, the reduction of the flux in the main core to zero at one load point is not essential to the operation of the transformer, and if in the transformer shown in Fig. 1, $R_b = R_c$ then the flux in the main core will not be zero at any load or any frequency.

The simplest explanation of the operation of the device as shown in Fig. 1 appears to me to be this. The transformer and compensator must be designed so that the magnetizing currents required by the cores may be considered as first-order small quantities compared to the primary current, I_p, the secondary current, I_s, and the compensator current, I_c; for if not, the compensator will not improve the performance of the transformer. Assuming that this condition is satisfied then the number of turns in the windings A, B and C ensures that the primary current, secondary current and compensator current can only differ from each other by first-order small quantities or less. Now, vectorially,

$$\begin{aligned} \text{E.M.F. in winding A} &= I_sR_b - \text{e.m.f. in winding B} \\ &= I_sR_b - I_cR_c \end{aligned}$$

(since e.m.f. in winding B necessarily equals e.m.f. in winding C)

$$\begin{aligned} &= (I_s - I_c)R_b \quad \text{if } R_b = R_c \\ &= \text{a first-order small quantity.} \end{aligned}$$

The magnetizing current required to produce an e.m.f. which is a first-order small quantity must be a second-order small quantity if the design condition mentioned above is satisfied. The ratio I_p/I_s and the phase angle between these two currents are principally determined by the value of the magnetizing current of the main core, and these errors are therefore second-order small quantities. Since no assumptions have been made

as to frequency or load it follows that the error of the transformer is small at all loads and frequencies within the working range of the two cores.

The author has therefore devised a transformer which has only second-order errors for all loads and frequencies within the working range at one burden. The change of error with change of burden would be greater than with an uncompensated transformer using the same total amount of material, but would in general be less than twice as great. In order to secure the full advantages of this transformer it is therefore necessary that it should be operated at its correct burden. In this connection, although it is clearly possible to limit the temperature rise of transformer windings to 20 deg C given by the author, a much higher figure is often realized in present-day practice. However, even if we accept the author's figure we see that if care is not taken the errors may change by 12% of the uncompensated errors. If a compensated transformer is designed to have an error not exceeding 3 min when cold, then the uncompensated error may be of the order of 50 min and the change of error of the transformer due to self-heating is then 6 min. In other words, the phase angle of the transformer is three times as great as would be expected from a "cold" test.

The author is undoubtedly right in suggesting that for ordinary commercial use the straight transformer will in many cases be found preferable. The more complicated device can be justified only when the desired performance cannot be obtained by a normal design except at prohibitive cost. He suggests that the principal applications will be standard precision transformers and low-ratio transformers, of which bushing transformers form a very important class. The errors of a standard precision transformer of normal design are very small, and although the errors may be reduced still further by the use of this device it is questionable whether that gain by itself would be sufficient to justify the change. The possible reduction in ampere-turns, and consequently in primary impedance, is often a further real advantage especially for step-up transformers. Capacitance- and leakage-reactance errors are also reduced when the ampere-turns are reduced.

The most promising application of the author's transformer is for bushing transformers of low ratio. These constitute a very difficult design problem for normal transformers. It is, however, a matter for regret that he should find it necessary to adopt premagnetization, which has serious disadvantages as he himself points out. A greater improvement of performance may be obtained in a better way, devised by Mr. Ockenden, namely by connecting a condenser across the terminals of a tertiary winding on the main core to supply the quadrature component of the magnetizing current. If the improvement of performance obtained by this device is insufficient, further improvement may be obtained by employing more than two cores. The general formula for the error of a transformer with n cores at one frequency is given below.

Let e_u = error of uncompensated transformer = vector sum of ratio error and phase-angle error

e_c = error of compensated transformer

n = number of cores

a = $\dfrac{\text{weight of core material in uncompensated transformer}}{\text{weight of core material in compensated transformer}}$

b = geometric average value for the n cores of the ratio

$$= \frac{\text{vector difference of magnetizing ampere-turns and condenser winding ampere-turns}}{\text{magnetizing ampere-turns}}$$

Then $e_c = (n^2 abe_u)^h$

This formula shows one of the principal advantages of the author's device, namely the possibility of obtaining a substantial improvement of performance by a moderate increase in the weight of material used. In this respect the advantages are comparable with the advantages obtained by using a string of insulators instead of one large insulator.

Mr. F. E. J. Ockenden: I am inclined to dispute that the so-called main-current transformer could ever in practice work under conditions of zero flux. However accurately compensated the transformer may be, the secondary current can never be completely in phase with the primary. Under such conditions, there is a small balance of ampere-turns available from this transformer which introduces the necessary corrective effect, and injects into the secondary circuit the minute current required to rectify the phase and ratio errors. Strictly speaking, the compensating transformer is doing most of the work and the other, the main transformer, provides the compensation. But both of these must be reasonably good transformers to start with, or the errors will get out of control.

I suggest that the theory of the transformer would be more easily understood and precisely similar results obtained, if the compensator winding C were omitted and the compensating resistance R_c placed as a shunt across the 50-turn winding B. It then becomes apparent that the magnitude of the current through R_b could be adjusted to precisely its correct value by suitable choice of the magnitude of R_c, the function of the transformer A remaining unchanged. This would have the further advantage of considerably simplifying the mechanical construction.

In Section 5.1, the author deals only with round quantities, and not with any of the second-order factors, such as I_m and I_L, which are so important in current-transformer design. In Section 5.2, on the performance of bushing-type current-transformers, the author has worked out exponents for the magnetizing current for Stalloy and Mumetal. To my mind, the simplest way of designing a current transformer is not to employ the usual curves, but to have two sets of curves prepared, one showing the core loss in W/lb and the other in VAr/lb. The vector relationship between these two quantities and the total power from the transformer then gives in the simplest possible manner the ratio and phase errors of the transformer and also the effect of changes of design on these quantities.

Mr. S. Howarth: I am glad that the author has drawn attention to the large errors which may be incurred due to inaccurate methods of estimating voltage-transformer errors. Most people using three-phase transformers use approximate methods which are not based on any mathematical theory, and in many cases corrections are not even applied at all. In high-voltage installations, considerable sums of money are involved in unit and demand charges and it is important, therefore, that the errors of the voltage transformers at the working burden are accurately known.

Contrary to the author's statement in Section 3.1, my experience is that it is more usual for the manufacturers to supply only line-to-line ratio and phase errors at two unity power-factor burdens. There are still many voltage transformers connected "on circuit" for which only this information is available, and it may not always be possible to remove them in order to carry out the special tests, referred to in the second method described in the paper. It may be possible to calculate the working-burden errors without these special tests, by resolving the line conditions into phase conditions, applying the M. and G. diagram in the manner described in the paper and then converting back to line-to-line results for the final figure. The calculation assumes a fixed position for the neutral point at the centroid of the line triangle. As a matter of fact, Mr. Bryce, of the Bradford Corporation Electricity Department, and I have been working on

some such calculation for some time past and the test results appear to agree very closely with the calculated figures, but we are not yet sure how the results would compare if the neutral were considerably displaced. I should like the author's views.

In the course of the calculations, we have developed formulae by means of which a rapid check can be made on the test data relating to any pair of lines to see if the resultant is equal to the data supplied for the third line. It will be agreed that the vector sum of the three line-to-line secondary voltages of a three-phase star-star voltage transformer must be zero. Secondly, the vector sum of any pair of lines must be equal to that of the third line, but reversed in sign. Assuming the order of phase rotation to be A–B–C, and the line-to-line vectors AB, BC and CA, the percentage ratio errors are denoted by: r_{AB}, r_{BC} and r_{CA}, and the phase errors in minutes by ϕ_{AB}, ϕ_{BC} and ϕ_{CA}. Then the percentage error $r_{CA} = \frac{1}{2}(r_{AB} + r_{BC}) + 1/40(\phi_{BC} - \phi_{AB})$, and the phase error in minutes $\phi_{CA} = \frac{1}{2}(\phi_{AB} + \phi_{BC}) + 30(r_{AB} - r_{BC})$.

Referring to the final figures of method (i) in Section 3.1, and substituting the errors of lines AB and BC in the equations, we obtain for line CA a ratio error of + 0·410% and a phase error of + 43·6 min, compared with the author's figures of + 0·413% ratio error and + 43 min phase error. This is close agreement and proves that the line vectors do sum to zero.

It is of interest to note that we have checked the figures on quite a number of test certificates by the same means, and in several instances there were considerable discrepancies, proving that either the test equipment was wrong or an error had been made in the measurement. We consider that the use of the formulae will assist greatly in the detection of wrong tests or wrong calculations.

In Section 3.1, it is also mentioned that in a normal transformer the three legs will be of identical design, so that to a sufficiently close approximation their resistance and leakage reactance will be equal and, in consequence, the changes of error for a given burden at unity power factor will be the same for each leg and only one M. and G. diagram need be drawn for the whole transformer. There are many transformers, perhaps of inferior design, which do not give equal changes of error for a given change of burden, and in these circumstances it may be incorrect to use only one diagram as mentioned. I would like the author to give an opinion as to how much discrepancy in the regulation can be introduced without affecting the accuracy of the calculations by using one diagram.

Mr. G. A. V. Sowter: The paper is most comprehensive in its treatment of instrument transformers and gives information on the good results achieved by the author's compensating device. His object has been to reduce errors by minimizing effects of loss and magnetizing ampere-turns on the ferro-magnetic core. Mumetal which is favourably mentioned in the paper, was introduced into instrument-transformer technique by reason of the low magnetizing force required to create the necessary flux. The author mentions 2 000 gauss as the working flux density which is rarely exceeded in instrument-transformer design. Values greatly in excess of this are employed with Mumetal and an induction of 4 000 gauss is quite common in some current transformers. On occasion even 6 000 gauss is specified. In some instances Radiometal is used for these transformers, advantage being taken of its higher saturation induction. It should be mentioned that nickel-iron alloy cores for instrument transformers are by no means restricted to 50-c/s operation. Mumetal cores are very satisfactory in the audio-frequency range, and are commonly employed in conjunction with oxide rectifiers.

It is not generally known that Rhometal in the form of thin strip spiral cores has been successfully utilized for aerial current transformers for frequencies of 1 Mc/s and above. Mr. W. Phillips designed and manufactured these transformers about 10 years ago and their performance was quite satisfactory. Recently the Engineering Dept. of the B.B.C. have made further measurements on Rhometal for this purpose.

The question of pre-magnetization has been raised and offers certain advantages. With Mumetal the maximum permeability occurs around B_{max} = 3 000–4 000 gauss, so that obviously the superposed working flux must be limited in view of the saturation induction of this alloy. Is it definitely established that losses are reduced by this method of operation? The increased permeability is apparent, but at first sight it appears that since the watt loss is proportional to B^n (where B is flux density and n may be of the order of 2), a change of B from 0 to 500 gauss creates less loss than one from 3 000 to 3 500 gauss. I am not disputing that there may be something to be gained by pre-magnetization, but the reason for the advantage in connection with iron-loss errors is not clear. Can the author give us more information?

The crowding of flux round the inside of cores having large ratios of outer to inner diameter is borne in mind when testing Mumetal cores in order to deduce basic properties of the alloy or for precision measurements. The variation of 50-c/s permeability of Mumetal with H is definitely less than that of silicon iron, but the fact that the H required for saturation of Mumetal is relatively small should not be overlooked. It is not clear from Fig. 4 or from the text what is meant by relative flux densities at different diameters for fixed ampere-turns through the core. The permeability of Mumetal is greatly in excess of that of Stalloy, but Fig. 4 could be interpreted to mean that at a diameter 2 the permeabilities are equal.

The Arnold test gear for calibrating instrument transformers has been of great value for current-transformer testing, and the author has extended its use to cover voltage transformers. The equipment can also be used for grading Mumetal cores.

Mr. A. Glynne: Fig. A shows a method, employing only

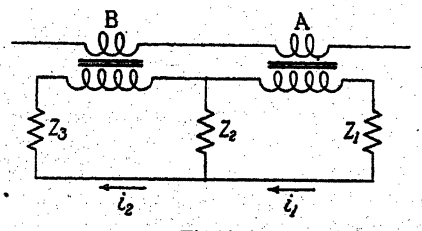


Fig. A

ordinary laboratory apparatus, of reducing the errors of a current transformer to zero. It is simpler than that described by the author; does he think his compensator has any advantages over this method? In the Figure, A is the main, and B the compensating, transformer. If $Z_2/Z_1 = i_1/(i_2 - i_1) = T_B/(T_A - T_B)$, there will be no flux in A and, therefore, no errors.

Dr. Arnold points out that, in the author's circuit, the two transformers must be of comparable quality, but it may be noted that in the method of Fig. A transformer B can have much larger errors than transformer A. If a burden Z_3 be included in the secondary circuit of B, as shown, the elimination of the errors in A is scarcely affected. Transformer B can hence be made to perform additional duties; for example, to operate protective relays.

A current transformer used in a "circulating-current" protective system has to be accurate under conditions of through fault at currents of, perhaps, 20 times full load. This condition is difficult to satisfy when the full-load ampere-turns are few, because the core tends to become saturated. If transformer B in Fig. A is constructed with a Stalloy core of substantial section and transformer A with a Mumetal core, the difficulties should be overcome.

The author has not explained how the impedance of the burden in the winding C of his compensator is to be adjusted. An

ideal method is to wind a search coil on the core of A and to adjust the impedance Z_C until a vibration galvanometer connected to the coil is brought to rest. By this means, the adjustment can be made whilst the transformer is in service, and it may be rechecked at any time without taking it out of circuit.

Mr. L. B. S. Golds: The author's method of reducing current-transformer errors is a most useful and timely contribution to current-transformer design in view of the recent rapid growth of short-circuit currents on high-voltage circuits; it is particularly applicable to metering current transformers with wound primaries and low ratios, e.g. 10/5.

The author does not stress sufficiently the necessity with these transformers for careful matching of the burdens on the compensator and secondary to obtain the highest accuracy. In fact, the lower the ampere-turns available the more necessary is it to ensure close compensation at the working burden. Assuming there is no difficulty in incorporating the usual test windings in these transformers, then it is a simple matter to adjust the compensating burden for the leads, meters and instruments after installation, using a portable current-transformer testing set, the whole equipment being tested thereafter with a 3-phase portable test equipment.

With regard to the figures which the author has given for the errors of star-connected voltage transformers, the organization with which I am associated usually install two single-phase transformers in one tank connected in open-delta to supply the voltage coils of 3-phase 3-wire meters, and to avoid those difficulties which the author envisages.

Dr. E. Billig: Having taken some part in the development of cross-magnetization, which is the special type of pre-magnetization shown in Fig. 3(*c*), I am interested in the author's proposal to combine this with his method of compensation. Could he illustrate quantitatively how much of the improvement in the performance shown in Table 4 is due to pre-magnetization?

The principle of pre-magnetization is relatively less effective with Mumetal as the permeability curve has a rather sharp maximum, and a slight variation in the amount of pre-magnetization might have the effect of reducing the effective, i.e. the incremental, permeability and raising the errors considerably above the minimum obtainable.

The theory of the compensated current transformer as given in Section 1.1 cannot be correct. If, as suggested, the flux in the main core is zero, that core could be made very small, and indeed it could be removed altogether, without affecting the performance. Stated differently, as there is no voltage induced in the secondary winding on the main core, that winding could be removed and one would be left with the compensating core alone carrying two independent secondaries, one loaded with the meter and the other with the compensating burden. It is obvious that with two parallel windings the currents may be shifted at will and it becomes possible to make the current in the winding connected to the meter correspond exactly to the primary current in magnitude and phase. This, however, holds good for one particular load only. As soon as the burden is changed the winding on the compensator will fail to supply exactly the voltage required by the meter and it is then that the main core will have to do the rest.

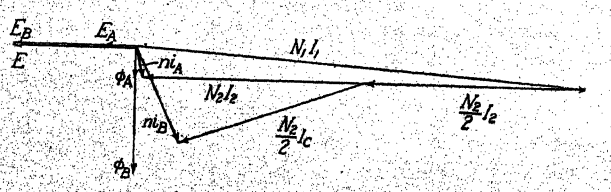


Fig. B

The mode of operation of the current transformer can best be explained by means of the vector diagram which has been drawn for a unity-power-factor load. The main core is excited by ampere-turns which are the vectorial sum of $ni_A = N_1I_1 + N_2I_2$, whilst the compensating core carrying 3 windings is excited by $ni_B = N_1I_1 + N_2I_2/2 + N_2I_C/2$. These excitations produce magnetic fluxes ϕ_A, ϕ_B and induce voltages in the windings which are in phase, hence the terminal voltage $E = E_A + E_B$. Using standard methods of current-transformer design, an equation for the ratio and phase error can easily be written down with the following result: Compensating core: operating on full primary ampere-turns loaded with burden $2r$. From this find the ratio error f. Main core: operating on full primary ampere-turns, loaded with burden $2rf$. From this find final performance (ratio and phase error). Being loaded with a very small burden, the main core always operates at a very low density of a few gauss only, and therefore should have a high initial permeability. On inductive load, the ratio error of the compensating core, f, and hence the effective burden on the main core, $2zf$, becomes larger, hence the overall performance is not quite so good (compare results for unity power-factor and 0·8 power factor in Table 1).

The same treatment can easily be applied where the compensating burden is not exactly equal to the external burden. The resulting errors are then made up of two components, one very small as described above and an additional component which corresponds exactly to that of an ordinary current transformer loaded with the excess burden, i.e. the difference between external and compensating burdens. This behaviour can immediately be verified by considering the two limiting cases of short-circuiting (1) the external burden or (2) the compensating burden. In both cases the current transformer will operate as an ordinary current transformer loaded with the same burden r.

Mr. C. F. Pizzey: In my opinion the practice of striving to reduce ratio errors to a few parts in 100 000, and phase-angle errors to tenths of a minute, shows lack of a sense of proportion. A current transformer is not in itself a measuring device, but must be used with an instrument or meter. When the transformer errors are reduced to the point where they are not discernible on the instrument, or are less than its inherent inaccuracy, there can be no object in reducing them further. This point may be taken as 0·025% of full-scale deflection for instruments, and 0·05% of full load for meters. In general, these requirements can be met by current transformers of conventional design, and I consider that special designs, such as that described by the author, are only justified if they succeed where conventional design fails, e.g. transformers with low ampere-turns.

Mr. J. W. L. Kojranski (*communicated*): A method somewhat similar to the modification of the Arnold bridge for testing voltage transformers has been developed with considerable success (Fig. C). In this method, the secondary voltages of the two

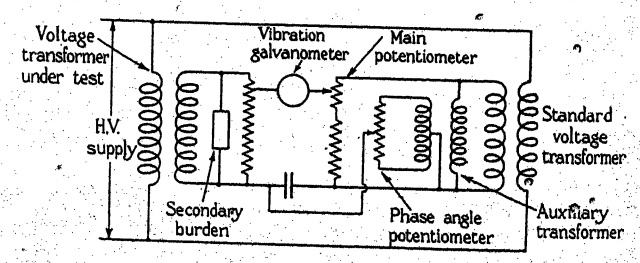


Fig. C

voltage transformers are compared through an a.c. potentiometer. The in-phase component is compared by means of a resistance potentiometer circuit, while the out-of-phase component is balanced by the voltage across a capacitor, fed from an auxi-

liary transformer connected across the secondary of the standard voltage transformer, through a potentiometer and series resistance. The auxiliary transformer has a centre-tapped secondary and imposes a burden of approximately 1 VA. The phase-angle error of this transformer does not affect the accuracy appreciably, provided that its cosine is close to unity (i.e. not more than 2 or 3 deg). The value of the potentiometer resistance, together with transformer ratio is determined by the range of phase angles required to be covered by the bridge. The transformer is centre tapped to allow for positive or negative phase angles. A large resistance is connected in series to bring the voltage across the capacitor in quadrature with the in-phase component of secondary voltage. The capacitor itself forms an integral part of the main potentiometer circuit. The idea of using a capacitor instead of a mutual inductance in a.c. potentiometer circuits appears uncommon in spite of its many advantages. Besides low cost and simplicity, a linear law is obtained and consequently the phase-angle error scale is uniform.

A resistance of the same value as the main potentiometer is connected across the tested transformer secondary, and a point away from its end is chosen to be connected through the vibration galvanometer to the main potentiometer slider. This arrangement dispenses with the need for changing over the standard and tested transformers in the event of the tested transformer having a positive ratio error. As the burden imposed on the standard transformer is approximately 5 VA at 0·9 power factor, which can be allowed for by calibrating the standard originally at this load, the change-over could not be carried out without putting excessive burden on the tested transformer. The total burden imposed on the tested transformer is 0·115 VA; this enables tests to be carried out at 10% of secondary burden at 0·2 power factor on 50-VA voltage transformers as required in B.S. 81: 1936. This has not been possible with certain types of testing gear. With the various components adjusted to give a range of ± 2·5% ratio error and ± 28 min phase-angle error a sensitivity greater than 0·005% and 0·2 min can be obtained.

Mr. H. S. Petch (*communicated*): It appears from Fig. 14 that in adapting the Arnold current-transformer testing set, the author is in fact employing only the mutual inductance and low-variable-resistance parts of that apparatus. As these are probably costly components, it is clearly reasonable to avoid the duplication resulting from the provision of separate testing apparatus for voltage transformers.

Having produced a relatively simple arrangement for testing current transformers (British Patent No. 527143) which avoids the use of a mutual inductance, we considered the obvious possibility of extending its use for testing voltage transformers. It was concluded, however, that the complication was not justified, and a separate set was developed, arranged however to make use of the same vibration galvanometer as in the current-transformer set. This apparatus (British Patent No. 543748) has certain advantages over that described by the author. It can, for example, be used to compare voltage transformers whose nominal ratios differ, as there are a number of standard voltage transformers still in existence in which the secondary voltage is 100.

The elimination of the mutual inductance is of real benefit, as the apparatus can then be made free from the effects of stray fields and can be made portable. With a portable set it is usually not difficult to test both current and voltage transformers on site with their actual working burdens, thus avoiding the calculations of Section 3, with their serious risk of errors in the hands of people to whom they are only a necessary nuisance.

In developing the testing sets mentioned above, it was observed, and may be worth emphasizing, that the vibration galvanometer is an unusual instrument in that it produces a back e.m.f., and that to obtain the maximum sensitivity of the instrument the impedance of the circuit feeding it must be nearly matched to that of the galvanometer. It is therefore an advantage to employ a type of circuit in which the galvanometer is supplied from a transformer winding, as the number of turns can then be adjusted to the best value.

Mr. H. D. Hawkes (*communicated*): Methods of testing current and voltage transformers by the comparison method against standard transformers, such as the Arnold and Petch–Elliott, invariably employ vibration galvanometers as "out-of-balance detectors." These galvanometers are tuned to fundamental frequency and give detection of the fundamental "out-of-balance" only. Under conditions of test which take no account of the harmonic content of the difference voltage or current of the two transformers, it appears somewhat bizarre to quote errors to an accuracy of 1 part in 100 000, even when tested on a "circuit of wave shape approximating closely to a sine wave."

The author has undoubtedly introduced a device which will greatly extend the scope of low-ampere-turn transformers, and it would be of great interest to know if the production of, say, 10 or 20-ampere-turn transformers of 5 or 40-VA burden, Class B, is a commercial possibility. With regard to the compensation of high-ampere-turn Mumetal current transformers, I am of the opinion that this is unnecessary.

The main purpose of the standard current transformer is for use with a standard wattmeter, on which the greatest accuracy of measurement is limited to 0·05% of nominal VA. This corresponds to an error of 5 parts in 1 000 at 1/10 load, or approximately 3·5 min at a power factor of 0·2. A transformer which will produce no apparent error when used with this highest class of instrument, can readily be designed without compensation.

Mr. O. Howarth (*communicated*): In Section 3.1 the author says that manufacturers usually give the errors of each phase to neutral of a 3-phase voltage transformer. Most of these transformers do not have their primary neutral brought out. Do manufacturers usually make their tests before the transformers are finished off?

Has the author evidence for his statement that the neutral displacement caused by unbalanced burdens is so small as to have no appreciable effect on the errors? My experience indicates that the characteristics of voltage transformers vary very much with the primary voltage and that what is true of one voltage is not necessarily true of some other voltage, owing, presumably, to the resistance of the primary winding being influenced by the minimum size of wire which itself is partly determined by mechanical considerations.

The author's method of determining the working errors of a 3-phase voltage transformer is interesting, but I would like to see proof of its legitimacy for various designs and voltages. He appears to assume that the conditions of loading on one leg do not appreciably affect the errors on either of the other two legs. On this assumption one would not expect phase rotation to affect the errors at zero or a balanced burden, but it does on some 3-phase voltage transformers. My view is that the simplest way of determining the errors at the working burden is to test at that burden, if known, as it usually is. It is our practice to test at zero, working and 100- or 200-VA burdens. Our voltage transformers for metering are invariably single phase, these being a cleaner job. Two are frequently mounted in the same tank which has three h.v. terminals.

THE AUTHOR'S REPLY TO THE DISCUSSION

Mr. A. Hobson (*in reply*): It is interesting that three experts on current transformers, Dr. Arnold, Mr. Ockenden, and Dr. Billig, have each offered "simplest" explanations of the operation of my compensator, and that all three differ. I think the old method I followed of describing an ideal case first and then discussing the deviations due to practical conditions, makes its operation easier to understand. The function of the main transformer is, I think, clear from the text, since winding A fixes, substantially, the current in B, while C has to take the "left-over" ampere-turns on the auxiliary core. Dr. Arnold's point that the reduction of flux to zero is not essential, is explained in Section 1.3, and the fact that R_b is equal to R_c does not quite give zero flux is indicated in Section 1.2.

Regarding temperature rise, the change in error of a compensated transformer is about the same as for the uncompensated one. It would not, of course, be right for a manufacturer to supply a transformer as being Class AL, if its natural error were about 50 minutes, without informing the customer of the fact. Standard precision transformers with over 500 ampere-turns may be compensated with only a little extra Mumetal or Stalloy. Coupling this with the advantage of reduced ampere-turns, and recent commercial experience, I see a much greater application for compensation in this direction than does Dr. Arnold.

I am not in the least contrite about using pre-magnetization. Its drawbacks, used by itself, do outweigh its advantages, but applied to the main core of my compensator, which carries very little working flux, I consider it may prove quite useful. Mr. Ockenden's condenser device would be of little value on low-ratio bushing transformers owing to the large capacitance needed, but it certainly works well on precision transformers.

In reply to Mr. Ockenden, I am sure that the flux in the main core can be reduced to zero for one value of burden, load current and frequency. I do not see how the main transformer can be considered to inject a small current into the secondary circuit, since it supplies all the current. A more elaborate theory of the compensator could easily be worked out, but practical conditions do not justify it. Using the simple theory given in Section 1.1, errors are reduced to a few per cent of their former values. To secure any further benefit would need a very great deal of extra work, culminating in the design of a compensating impedance which would probably have enough inherent errors to vitiate the whole procedure.

If a three-phase transformer showed error changes of, say, 10 and 7 minutes on two different legs for the same burden, using only one M. and G. diagram would introduce errors of about 3 minutes in the final calculations.

Pre-magnetization does reduce the loss ampere-turns; the exact reason for this still awaits elucidation. I do not think that anyone even remotely acquainted with the properties of Mumetal would misread Fig. 4 as Mr. Sowter suggests.

Mr. Glynne's method of compensation is an obvious development of my own, and has been suggested by Mr. Ockenden. It has been used by my firm for some time, and the impedance Z_2 used to operate relays. The burden Z_3, is thus redundant, and moreover increases the errors of the compensator. In practice my original connection in usually preferable, because the ratio of turns in B and C may be chosen so that the relay burden provides just the right compensation.

Mr. Glynne's idea of a search coil on the main core is a very good one, although I think a small rectifier-voltmeter could be used in place of the galvanometer. As Mr. Golds assumes, it is quite simple to fit test windings on compensated transformers, but I think Mr. Glynne's idea is easier than using a portable current-transformer testing equipment.

Mr. Golds is correct in saying that the use of two single-phase voltage-transformers is simpler when only two phases are to be loaded. If, however, there is a burden on all three phases, the calculations are still more involved.

In reply to Dr. Billig, Table 3 gives the effect on my compensation only. Table 4 gives the combined effect of compensation and pre-magnetization. In criticizing Section 1.1, Dr. Billig has ignored the succeeding Sections, which explain the points he raises. His own theory is, of course, mainly correct, but he is wrong in comparing the results for unity and 0·8 power factor in Table 1. These figures are obtained with the same compensation in each case. An adjustment in the power factor of the compensation would produce almost the same performance for 0·8 as for unity power factor.

Mr. Pizzey's view is short-sighted, and he ignores the benefit of negligible errors in integrating instruments, while compensated standards are finding increasing use in current-transformer testing.

Mr. Kojranski's method is interesting, but it is not applicable to the Arnold set.

It is easy to provide a 100-volt tapping on a standard voltage transformer, nullifying the advantage claimed by Mr. Petch. Regarding portability, I think the Arnold equipment could be made much smaller. Mr. Petch exaggerates the effects of stray fields, which can be made negligible by simple precautions.

The effect of harmonics on the errors of instrument transformers, are not nearly so great as Mr. Hawkes imagines. For transformer No. 1 at 5 VA, the magnetizing current is about 0·15%, and assuming this has a 30% third harmonic, the harmonic content of the magnetizing current is 0·05 per cent of the input. The effect of this on the r.m.s. value of the fundamental is 0·05% of 0·05%, about 1 part in 4 000 000.

In reply to Mr. O. Howarth, Mr. S. Howarth has had the opposite experience to mine regarding test certificates, and he has probably seen more than I have. Regarding neutral displacement, transformer theory shows that the neutral of a 3-leg 3-phase star transformer is stabilized at the centre of the line triangle, except for unequal impedance drops in the windings. In a voltage transformer, the drops do not exceed 2 per cent, which is therefore the maximum neutral displacement to be expected. I have been unable to move the neutral appreciably in practical tests. I maintain that the loading on one leg hardly affects the errors on the two other legs. This statement does not clash with Mr. Howarth's experience regarding phase rotation, which is probably due to unequal reluctances in the magnetic circuit. Mr. Howarth is fortunate in being able to test his transformers at working burden, which of course is the ideal solution. Most meter departments do not have the necessary equipment.

DISCUSSION ON "STANDARDIZATION OF DISTRIBUTION IN DENSELY LOADED AREAS"*

SCOTTISH CENTRE, AT EDINBURGH, 14TH APRIL, 1943†

Mr. P. d'E. Stowell: Three main principles are put forward in this paper, namely the distributed transformer arrangement, the solid lower-voltage network and the policy of standardization. The first of these is the most important, as it accounts for the bulk of the improved financial results shown in Table 2. I should like to recommend for general adoption the term "single-unit system" instead of "distributed-transformer system," and "multiple-unit system" for "group-transformer system." This alternative nomenclature, besides being of more general application, is also a better description of the fundamental difference between the two systems.

It is surprising that the single-unit system has not been very much more widely adopted in the public electricity supply industry. The extensive use of the multiple-unit system is no doubt largely a continuation of a practice built up in the era when direct current was popular. This practice consisted in providing spare plant at all locations at which plant was installed. Thus a minimum of two units at any point was considered essential to provide this standby. For d.c. plant which had to be attended, as much grouping of the plant as possible was a wise policy because it reduced the number of sites to be attended. The cost of attending distributed d.c. plant would have been prohibitive.

In the case of transformer plant for a.c. supplies, continuous attendance is entirely unnecessary and this cost disappears. The total capital cost and distribution losses then assume a much greater importance. Moreover, in city distribution and in fact generally, the lower-voltage system is invariably a complete network capable of interconnecting all the feeding points. It is thus reasonable to install single units throughout and to arrange that the standby facility is provided as between one unit and its neighbours over this network. By so doing it is ensured that all plant is effective in keeping losses at a minimum and guaranteeing good voltage regulation. With the multiple-unit system the only useful function performed by a considerable proportion of the plant is the standby duty. Also the multiple-unit system frequently leads to a state of affairs in which the total amount of plant installed at any location becomes excessive. This reacts unfavourably on the amount of copper required in the lower-voltage network, as considerable lengths of l.v. feeder become necessary and these cannot be regarded as serving any useful purpose.

Whereas in railway traction supply it is generally agreed that it is wrong to install more than one unit at any one point on the network unless the load at that particular point is greater than the permissible loading of the size of unit standardized, the public electricity supply authorities have in general not yet reached this conclusion. Large multiple-unit a.c. substations are still being installed, and a fairly recent one that I have in mind contains four 1 000-kVA transformers to feed a 400-volt city network with a fairly dense load. It has 15 l.v. feeders of an average length of 220 yd. The average length of the distributor network is 422 yd. per feeder. The feeders therefore increase by 52% the length of copper that would otherwise be necessary, and the weight of copper added by them is just over 69%. When the system is fully loaded the feeder losses amount to 40 watts per yard. Each feeder therefore wastes 8·8 kW, and the 15 feeders thus dispose of 132 kW or 3·5% of the capacity of the substation. Assuming a reasonable load factor these losses at Grid tariff would cost at least £800 per annum. The capital charges on the feeders add another £300. Had a suitable single-unit system been installed the saving in these annual costs unquestionably would have over-compensated any possible increase in cost of substation plant. Criticism of such excessively large substations only brought forth the argument that it is difficult enough in a city to obtain sites even for the minimum number of substations. The paper shows that such an argument is not in fact valid.

The solid lower-voltage network proposed by the author is best compared with two alternatives. The opposite extreme, which is frequently found in practice, is a system operated in entirely separate sections associated with each substation or even each l.v. feeder. An intermediate arrangement is a network completely interconnected, but through fuses.* The solid and interconnected networks have a small economic advantage over the other system, on account of lower losses and better voltage regulation.

If the criterion of reliability is examined it is found that sectionalized networks and fuse-interconnected networks have an apparent advantage in that the area affected by any individual fault is positively restricted. The process which brings about this restriction also ensures that the mains engineer is left in no doubt about the existence of any fault, because some consumers are bound to lose their supplies. The advantage is doubtful, however, because a solid network by burning off the faults could under ideal conditions clear most of them without affecting any consumers. In fact, the average number of consumers affected per fault is a good measure of reliability. For a sectionalized system this figure cannot very well be less than the average number per section, say 100; for a fuse-interconnected system the minimum is of the order of the average number of consumers between link boxes, say 20, whereas for a solid system the theoretical lower unit is almost zero. There is no doubt that the main factor which prevents wider adoption of the solid network is the fear of a fault failing to burn clear and thereby affecting the supply to a comparatively large area. Could the author quote some comparative statistics for solid and sectionalized networks of average fault severity over a period of years? These statistics might be in terms of consumers, consumer-minutes or kWh affected per fault.

Finally, I agree that there is much to be gained by a policy of standardization, provided that is it not allowed to restrict future development in any way. An established policy, too, is much to be preferred to the perhaps more usual method of considering jobs on their merits. This usually results sooner or later in a heterogeneous collection of different installations, and not infrequently the small initial economy of a non-standard job is more than offset by considerably increased expense incurred in alterations later. As an example of pure standardization, the method of using two h.v. switchgear units coupled together, as shown in Fig. 3, is interesting. Too many engineers would prefer to use a special unit having the two oil circuit-breakers on one set of busbars, in order to save the cost of two oil switches. Besides using standard equipment the author's arrangement, though perhaps slightly more expensive, has some subtle technical advantages,

* See B. WOOD: *Journal I.E.E.*, 1942, 89, Part II, p. 400.

* Paper by Mr. J. W. LEACH (see *Journal I.E.E.*, 1941, 88, Part II, p. 525).

† In the absence of the author the paper was read on his behalf by Mr. J. Whitcher.

Mr. J. Eccles: It may perhaps be said that the author is fortunate in having such a compact and heavily loaded network. His area of supply is 6½ square miles and his maximum demand is of the order of 200 000 kVA. Every inch of street is occupied by important buildings, most of which are commercial buildings. By contrast, the Edinburgh undertaking covers 50 square miles and has less than half this maximum demand. It must therefore include areas to which there cannot be applied the considerations which the author can bring to bear upon the whole of his network.

The main criticism I wish to offer is that the temporary loss of six 500-kVA transformers for a single high-voltage cable fault may be an unwarrantable dislocation, particularly as there is apparently no automatic indication as to which section of the cable is faulty. Time will tell whether or not this is a valid criticism, and particularly so as faults become more numerous with the ageing of the h.v. network.

The author has adopted the unconventional practice of placing fuses between sections of network instead of at the points of supply, and I should be very interested to learn of any operating experience accumulated since this method was introduced.

One saving which is likely to accrue from the author's method is a reduction in distribution losses; if he has any comparable figures for the losses in a block of network under the old radial type of distribution as compared with his distributed-transformer scheme, I should be glad if he would give them in his reply.

Finally, I should like to see some kind of forum established where supply engineers could exchange information on experiences. A kind of clearing house is required where the details of every major experience would be available exactly as it was recorded at the time of the occurrence and before anyone had had time to theorize upon it. This, together with a record of the action taken and the results achieved, would, if available generally, be a tremendous asset to the supply industry.

Mr. W. W. Martin: I agree with the author that standardization of the requirements for substation equipment will contribute largely to a reduction in the cost of such equipment, but I would suggest that only the requirements be standardized and that dimensions or design details should not be specified by the purchaser of the equipment as this tends to retard the development and the improvement of designs. The author suggests that 150-MVA switchgear offers the highest value for money, and the reason is probably that undertakings have largely standardized on this size and the volume of production is thus greater than for other sizes.

In the paper there are numerous references to the useful life of equipment: I should like to know the significance of this term, particularly in relation to switchgear. To manufacturers the useful life of switchgear appears to be unending, no matter what improvements in design are introduced.

Considering the 11-kV fault values given by the author, I agree that 250-MVA switchgear is suitable for use where the fault value under emergency conditions is 273 MVA, but I suggest that when either two or three sections of the main substations are paralleled the fault values on the distribution-substation switchgear adjacent to the main station may be excessive. The area under consideration is densely loaded and the distances, therefore, are not great. Taking the author's standard cable sizes of 0·15 sq in at 11 kV and 0·25 sq in at 6·6 kV, a simple calculation will show that to reduce 273 MVA at the main station to 150 MVA at a substation fed over a single feeder will require 2·69 miles of 11-kV cable and 1·1 miles of 6·6-kV cable. I would therefore suggest that considerable risks are being run in paralleling sections at the main substations, since should a fault occur under these conditions the substation switchgear would be called upon to break a fault value of the order of 250 MVA, which is considerably in excess of its 150-MVA rating. It appears to me, therefore, that for densely loaded areas the high-voltage distribution switchgear should have the same breaking-capacity rating throughout the area, i.e. at the main and distribution substations.

With regard to the low-voltage fault value given in Section 1.13, I should have anticipated that it would have been greater than 25 MVA owing to the interlinking between sections of the l.v. network. Taking the maxmimum block as 12 000 kVA, as given in Section 1.11, and assuming this to be supplied through a number of 500-kVA (4% reactance) transformers having this total capacity from a 150-MVA network, then, neglecting cable impedance, the fault value on the low-voltage side will be 100 MVA. It seems inconceivable that the impedance of a solidly connected low-voltage network should be such as to reduce this value to 25 MVA. It is reassuring to find, however, that practical experience indicates that 25-MVA fuses are adequate.

Mr. H. C. Wellden: I should be glad if the author would give some information on the subject of the burning-off of faults. Faults emanating from cables themselves are so few in number that they can be practically neglected.

Cable faults may arise from the following three causes: (1) external damage, (2) the human element, (3) perforation of the lead sheath by electrolytic action.

A fault which is left to burn itself off may not be dealt with for some considerable time, and during this period the fault, or perhaps two faults, may periodically recur owing to moisture penetrating the cable ends. I can conceive of quite a long length of cable being damaged in this way. Can the author give any indication as to the average length of cable damaged when an open-circuit is eventually found?

There is also the question of faults occurring in cables drawn into ducts. If the fault gets back to a joint, where bituminous compound is present, an explosive mixture is almost sure to be formed, with disastrous consequences.

Mr. W. Easton: I have had some personal experience of the network under discussion, and I was much impressed by its straightforward layout. Over-elaboration of protective gear had been avoided and great care had evidently been taken to develop a design which would permit the use of standardized equipment of moderate capacity, thus ensuring the best possible value for the money expended. There is, however, a point of weakness in that no reverse-power relays are provided in the low-voltage air breakers for operation when a fault occurs on a high-voltage feeder.

The fault will trip the h.v. oil circuit-breaker in the distribution station, but the fault will still be fed from the adjacent sections through the inter-section fuses and thence through the transformers on the faulty feeder. These fuses will have to carry not only the load current on the faulted section but the fault current as well. It is more than likely that some of these fuses will blow, thus passing their load to their neighbours, causing these to blow in turn, until the supply to the section is completely interrupted.

Would the author give his views on the advisability of fitting reverse-power relays, to secure the complete isolation of the faulty feeder?

Mr. A. F. Stevenson: It is now standard practice to eliminate the l.v. feeders by placing substations where they are required by the local load. I remember a meeting of the Northern Society in the 'nineties when it was suggested that h.v. cables should be laid alongside the l.v. distributors, and, as the load increased, transformers should be inserted between them. The suggestion caused great amusement.

I am surprised that standardization has not been carried out in connection with cable sizes. Most supply engineers now use 0·25 sq in where possible, whereas the author also mentions the

use of 0·5 and 0·4 sq in. His stock of cable and fittings must be unnecessarily large.

Mr. C. E. Shaw: Obvious advantages of the distributed-transformer method are savings on account of l.v. copper and transmission losses, and also (if my deductions are correct) savings in respect of substation buildings and sites. While the ethics of the latter method of effecting savings may be open to a little criticism, such savings would form a considerable factor in the scheme outlined by the author.

Those of us who have experienced the difficulties and delays involved in obtaining substation sites in congested urban areas will be inclined to welcome such a comparatively easy alternative, and one is bound to agree that future developments in demand for electricity supply will necessitate the increasing use of transformers on consumers' premises.

It is suggested, however, with regard to this policy, that methods should be explored whereby security of tenure may be guaranteed.

The savings on account of substation equipment are not so obvious. For instance, six 500-kVA transformers would cost more to supply, install and maintain than three 1000-kVA transformers, and the minimum number of high-voltage panels required in the two cases would be 18 and 5 respectively.

I am aware that costs have been reduced by simplification of protective gear and the use of on-load isolators in place of feeder circuit-breakers, but of course similar curtailment of facilities could be applied to a group substation.

The figure of £750 mentioned by the author seems a low cost in respect of a 500-kVA transformer with associated h.v. and l.v. switchgear, and segregated costs of the components included would be of interest. Is it the custom to close isolators on to a possibly faulty cable? In one make of isolator which is supplied for use with 150-MVA switchgear, it has been found that to close on a concentration exceeding 30 MVA would be physically impossible to the average man.

The system of protection which the author describes appears to rely unduly on the immunity from breakdown associated with modern high-grade equipment. The l.v. interconnectors between adjacent areas would require to connect between the respective injection points, and have loading capacities equal to the injected load, to be of real service: and, even so, where the h.v. radial feeder supplying six 500-kVA transformers breaks down, the l.v. interconnectors will have to supply 9 000 kVA in order to supply the peak load and clear the fault simultaneously. It seems unlikely that such a standby arrangement would succeed, especially at peak-load time, when faults usually occur.

"Burning off" faults seems an easy method of getting rid of such embarrassments, but is this the end of the trouble? If not, what is the method of keeping track of affected cables, since faults may occur and burn-off without the knowledge of the operating staff? Are such incidents simply allowed to accumulate?

Despite their disadvantages, fuses would be useful in giving a clue to the positions and existence of faulty cables.

Mr. J. W. Leach (*in reply*): Many of the points raised have already been dealt with in my published reply to the general discussion, and restrictions on paper and space determine that I should not deal with them again.

Mr. d'E. Stowell has evidently given this matter of distribution systems serious consideration, and I note with interest his close confirmation of the system described. The overall cost of the grouped-transformer system, or, as he prefers to call it, the multiple-unit system, is more than that of the single-unit system as exemplified in Table 2.

I sympathize with him in regard to the lack of statistics on faults—so many engineers prefer to avoid publicity. This is natural, but it would be to the ultimate advantage of all engineers to exchange information on these matters. Since this paper was written I have had additional experience which may be of interest, concerning a l.v. system laid direct about 15 years ago, in which weakness permitted ingress of moisture. Deterioration was greatly accelerated by heavy air-raid damage and flooding, and 26 failures in the cable joints have occurred in this section since September, 1940. The boxes have failed mostly at services, but also on the distributor, and in every case the fault has burned clear without any disturbance of supplies to other consumers. This number of faults is, of course, exceptional and it is hardly necessary to add that the particular section of the network is being reconditioned.

In reply to Mr. Eccles, some parts of the area are by no means so densely loaded as others. Table 1 shows an area density of 16 000 kVA per square mile, yet the system operates equally well and shows all the advantages in practice. In making plans for the future it should always be borne in mind that the demand for electricity is steadily increasing.

There is no automatic indication of the position of possible faults on the h.v. distributor. Such a fault is rare in practice, even then it is likely to be an earth fault, which does not interrupt the standby supply from the adjacent l.v. networks. As Mr. Wellden points out, the position of cable faults is generally known from the start because they usually arise from mechanical damage or human errors, but I agree that an indication system which did not involve pilots or extra switchgear would be an advantage when breakdowns do occur. The practice of installing fuses in the l.v. network at points of no load is undoubtedly sound; the only operating experience required is the time taken to discover which fuses are affected after a disturbance, but, as the fuses are at points of negligible normal load, delay is of minor importance in this matter. I have no comparable readings of efficiency in terms of units purchased and units sold in a distributed-transformer area and a grouped-transformer area; such observations as I have been able to make confirm the superiority of the distributed-transformer arrangement, but do not give sufficient information to enable me to assess the magnitude. The superiority of h.v. transmission to l.v. transmission, combined with the elimination of the l.v. feeders, provides the clue to this improvement. I am glad to endorse Mr. Eccles's plea for proper fault records; these will often help to dispel the mistaken prejudices that sometimes grow up among staff regarding the performance of the system they are operating and at the same time provide valuable data upon which to base improvements of designs generally. The most important feature of such records is that they should be made as soon as possible after the occurrence and that all the relevant facts should be given, unsullied by theories and explanations of the cause.

I agree with Mr. Martin's view that the supply undertaking should standardize requirements rather than plant designs. This is what I have endeavoured to do, leaving a free choice in selecting those types of plant that best fill the requirements in the least space. Having by design of the distribution system stabilized the switchgear duty, one expects a life of the order of the conventional 25 years. I agree that it may in fact be longer. The question of switchgear ratings was dealt with in the original discussion. The many factors mentioned in Section 1.13 of the paper restrict the low-voltage short-circuit current. Our experiences tend to confirm that the network impedance in practice is far from negligible and that the short-circuit brought in through the interconnected network is about equivalent to that coming direct from the h.v. system through an individual transformer chamber. It is also of interest to mention that tests which were made on a resistance model to scale of a well-developed section of the network were in agreement with this, and the value of 25 000 kVA is assumed as one not generally exceeded. I think

Mr. Martin would agree that to provide at the fault a current equivalent to 100 MVA at 400/230 volts is a matter of some difficulty requiring special measures, even in a short-circuit testing station.

In reply to Mr. Wellden I would say that unless the fault kVA are very much restricted the extent of cable damage is purely local and there is no loss of cable such as he fears. On the other hand, on a network which was fused in the conventional manner (not yet converted to standard) we have recently experienced a fault which damaged some 30 yd of cable. The fault appeared to be an intermittent one of the nature suggested by Mr. Wellden; it blew certain of the fuses on the direct feed, but left others to supply the fault through such a length of cable that the fault was insufficient to blow the fuses. We have not experienced extensive electrolytic action on the a.c. system, but I think the possibility of such action where a.c. and d.c. systems are laid together is a strong argument for eliminating d.c. systems, where alternating current is available.

I am glad that Mr. Easton confirms the simplicity of the system described in the paper and speaks so well of his experience with it. With regard to reverse-power relays, theoretically this would be a correct application but such relays have in the past tended to be unreliable. They introduce further complications in the transformer-chamber equipment and also require provision for auxiliary tripping.

Mr. Stevenson suggests that the number of sizes shown in Figs. 7 and 8 is excessive. This is quite true. For all new work we have standardized on 0·3-sq in l.v. cables; the diagrams are of networks developed over a number of years, before standardization had been fully adopted. Where existing cables are not too small they are retained.

Replying to Mr. Shaw, where transformers are installed by the supply undertaking rather than by the consumer, the space and cost to the consumer is less, since a minimum of equipment is installed and standby is provided from the l.v. network. The consumer usually quickly realizes this and is only too willing to co-operate. There need be no anxiety regarding security of tenure, for as long as the premises require electricity the transformer must stay. If a supply is not required then the transformer is not wanted and can be removed: this, however, is a most infrequent occurrence.

The figure of £750 (pre-war) is correct, and I can furnish Mr. Shaw with the details. The ring-main isolators on the equipment used have been tested to make 150 MVA with hand operation. It is not the custom to close isolators on to a known fault, but they have on more than one occasion been closed without mishap on to earthed feeders by operators' mistakes.

I have already dealt with the subject of the burning-off of faults: I would not incur the cost of using fuses as indicators.

PROCEEDINGS OF THE SECTIONS OF THE INSTITUTION*

INSTALLATIONS SECTION

20TH MEETING OF THE INSTALLATIONS SECTION, 9TH DECEMBER, 1943

Mr. A. G. Ramsey, O.B.E., B.Sc.(Eng.), Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 11th November, 1943, were taken as read and were confirmed.

A paper by Messrs. W. Fordham Cooper, B.Sc.(Eng.), and F. H. Mann, Members, entitled "Industrial Fire Risks," was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

21ST MEETING OF THE INSTALLATIONS SECTION, 10TH FEBRUARY, 1944

Mr. A. G. Ramsey, O.B.E., B.Sc.(Eng.), Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 9th December, 1943, were taken as read and were confirmed.

A paper by Messrs. H. Barron, Ph.D., B.Sc., J. N. Dean, B.Sc., Companion, and T. R. Scott, D.F.C., B.Sc., Member, entitled "Thermoplastic Cables," was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

MEASUREMENTS SECTION

110TH MEETING OF THE MEASUREMENTS SECTION, 21ST JANUARY, 1944

Mr. E. W. Moss, Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 19th November, 1943, were taken as read and were confirmed.

The following papers by Mr. A. Glynne, M.A., Associate Member, were read and discussed:

"A New Electronic Stabilizer and Regulator for D.C. Voltages" and "The Use of a Simple A.C. Potentiometer for the Precision Testing of Instrument Transformers."

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

TRANSMISSION SECTION

56TH MEETING OF THE TRANSMISSION SECTION, 8TH DECEMBER, 1943

Mr. T. R. Scott, D.F.C., B.Sc., Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 10th November, 1943, were taken as read and were confirmed.

A paper by Messrs. C. O. Boyse, Member, and N. G. Simpson, Associate Member, entitled "The Problem of Conductor Sagging on Overhead Transmission Lines" was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

57TH MEETING OF THE TRANSMISSION SECTION, 9TH FEBRUARY, 1944

Mr. T. R. Scott, D.F.C., B.Sc., Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 8th December, 1943, were taken as read and were confirmed.

A paper by Mr. B. L. Metcalf, B.Sc., Member, entitled "Transmission and Distribution of Electricity to Mines," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

* Excluding the Wireless Section, the Proceedings of which will be found in Parts I and III of the *Journal*.

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PROCEEDINGS OF THE SECTIONS OF THE INSTITUTION*

INSTALLATIONS SECTION

22ND MEETING OF THE INSTALLATIONS SECTION, 9TH MARCH, 1944

Mr. A. G. Ramsey, O.B.E., B.Sc.(Eng.), Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 10th February, 1944, were taken as read and were confirmed.

A paper by Mr. Hamlyn Drake, B.A., entitled "The Influence of Maintenance Requirements on the Design of Electrical Installation Equipment," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

MEASUREMENTS SECTION

111TH MEETING OF THE MEASUREMENTS SECTION, 18TH FEBRUARY, 1944

(Joint Meeting with the Transmission Section.)

Mr. E. W. Moss, Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 21st January, 1944, were taken as read and were confirmed.

A paper by Messrs. L. B. S. Golds, Member, and C. L. Lipman, Associate Member, entitled "A Modern Earth-Fault Relay Equipment for Use on Systems protected by Petersen Coils," was read and discussed.

On the motion of the Chairman a vote of thanks, with which Mr. T. R. Scott associated himself on behalf of the Transmission Section, was accorded to the authors and was carried with acclamation.

112TH MEETING OF THE MEASUREMENTS SECTION, 17TH MARCH, 1944

Mr. E. W. Moss, Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 18th February, 1944, were taken as read and were confirmed.

A paper by Mr. R. Dell, Member, entitled "Developments in Railway Signalling on London Transport," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

113TH MEETING OF THE MEASUREMENTS SECTION, 31ST MARCH, 1944

Mr. E. W. Moss, Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 17th March, 1944, were taken as read and were confirmed.

A discussion, opened by Messrs. E. Fawssett and G. F. Shotter, Members, took place on "The Consumer's Supply Control Unit of the Future, and its Effect on the Design of the Electricity Meter."

At the conclusion of the discussion a vote of thanks, moved by the Chairman, was accorded to Mr. Fawssett and Mr. Shotter for their introductory remarks.

Mr. W. K. Brasher, the Secretary of The Institution, thanked the members who had taken part in the discussion and stated that their remarks would be of very great assistance to the Electrical Installations (Study) Committee, convened by The Institution on behalf of the Minister of Works, and to the appropriate Sub-Committees of the Codes of Practice Committee for the Electrical Equipment of Buildings.

TRANSMISSION SECTION

58TH MEETING OF THE TRANSMISSION SECTION, 8TH MARCH, 1944

Mr. T. R. Scott, D.F.C., B.Sc., Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 9th February, 1944, were taken as read and were confirmed.

A paper by Messrs. E. C. Neate, B.Sc.(Eng.), Member, and W. F. Bowling, Associate, entitled "Reinforced-Concrete Transmission Line Supports," was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

59TH MEETING OF THE TRANSMISSION SECTION, 28TH MARCH, 1944

Mr. T. R. Scott, D.F.C., B.Sc., Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 8th March, 1944, were taken as read and were confirmed.

A discussion, opened by Mr. P. E. Rycroft, M.B.E., Member, took place on the Supply and Distribution Sections of the Report on "Electricity Supply, Distribution and Installation," prepared by Sub-Committee No. 3 of the Post-War Planning Committee.

At the conclusion of the discussion a vote of thanks, moved by the Chairman, was accorded to Mr. Rycroft for his introductory remarks.

* Excluding the Wireless Section, the Proceedings of which will be found in Part I and also in Part III of the *Journal*.

A NEW ELECTRONIC STABILIZER AND REGULATOR FOR D.C. VOLTAGES*
AND
THE USE OF A SIMPLE A.C. POTENTIOMETER FOR THE PRECISION TESTING OF INSTRUMENT TRANSFORMERS*

By ARVON GLYNNE, M.A., Member.†

(*The first paper was first received 20th July, and in revised form 9th November, 1943; the second paper was first received 15th October, and in revised form 9th November, 1943. They were read before the Measurements Section 21st January, 1944.*)

PAPER No. 1: A NEW ELECTRONIC STABILIZER AND REGULATOR FOR D.C. VOLTAGES

SUMMARY

After reviewing the characteristics of the high-voltage supply which is required for use in meter testing stations established under the Electricity Supply (Meters) Act, 1936, the paper describes the construction and gives the theory of a stabilizer which has been designed to provide current at a voltage so constant that it greatly facilitates precision measurements on voltmeters and wattmeters. Some other uses for the apparatus are described.

(1) INTRODUCTION

Under the Electricity Supply (Meters) Act, 1936, each meter testing station must be equipped with a wattmeter of approved design which must be checked periodically by means of a d.c. potentiometer. From time to time the Electricity Commissioners issue regulations and advice for the help and guidance of those concerned. Very full and detailed instructions have been issued relating to the installation and use of the standard potentiometer and its accessories, including the apparatus for the supply and control of the necessary currents.

The following extracts are made; with the consent of the Chief Meter Examiner, from a circular which has been supplied by the Electricity Commission to all testing stations established under the Act.

"The high-voltage battery should have a voltage somewhat in excess of the highest voltage at which instruments are to be tested. Its capacity should be sufficient to ensure that the current supplied to the instrument under test, the voltage-dividing resistor, the standard voltmeter, etc., is steady to within 1 part in 10 000 over a few minutes and to within 1 part in 1 000 over half an hour.

"The high-voltage supply may be obtained from sources other than a battery provided that the above figures of voltage stability are complied with and the insulation is adequate . . .

"The high-voltage battery must be installed outside the standardizing room. . . .

"The means adopted for control of voltage applied to instruments under test must be sufficient to ensure that the voltage may be adjusted to any particular value within 1 part in 10 000. The voltage control must be stable for all values of voltage, and under all conditions of adjustment. . . ."

"Care must also be taken to avoid undue rises due to discontinuation of any of these items while others remain connected . . .

"The load normally supplied by the voltage supply should also be connected for an hour, to allow this source to attain a steady state. . . ."

The stabilizer which forms the subject of this paper has been designed to provide a substitute for the high-voltage battery in standardizing rooms, which complies with the requirements quoted above and avoids many of the troubles peculiar to secondary batteries. In its present form it is the equivalent of a battery with an internal resistance of about 2·5 ohms whose e.m.f. can be smoothly adjusted to within 1 part in 20 000 over a range of 80 to 600 volts. The voltage remains steady to within 1 part in 100 000 for a few minutes and to within 1 part in 10 000 indefinitely. Currents of more than 100 mA can be supplied. A much greater current output at a somewhat reduced degree of stability can also be obtained.

(2) PRINCIPLE OF THE STABILIZER

The apparatus consists of some convenient source of d.c. supply, to which is connected a valve stabilizing circuit. The latter absorbs 100–150 volts of the input and the remainder is delivered in a stabilized condition. The standard voltage against which the output is compared by the device is provided by a dry battery, which is not called upon to deliver any current and, consequently, has a very long life. It is desirable that the d.c. input voltage be adjustable, but the adjustment is not at all critical.

(3) SOURCE OF D.C. INPUT TO THE STABILIZER

The author uses a small, separately-excited d.c. generator, driven by a synchronous induction motor, as his source of direct current. The excitation is obtained from the 110-volt d.c. mains, but might equally well be provided by a separate exciter or by a rectifier (self-excitation would not be suitable). Alternatively, the direct current can be obtained from a rectifier. In this way the unit may be made portable and may be entirely operated from the 230-volt a.c. mains. A very satisfactory stabilizer has been constructed on these lines. If a high-voltage battery has already been installed in a testing laboratory it will form an excellent supply for the stabilizer and the stabilized output will be available without the usual delay.

(4) THE STABILIZER CIRCUIT

The essential circuit of the stabilizer is shown in Fig. 1. It consists of a valve V_1 connected in series with the load, together with a second valve V_2 whose function is to provide the grid of V_1 with the correct potential to maintain the output voltage of the stabilizer at a nearly constant value. The grid-to-cathode voltage of V_2 is equal to the output voltage minus the constant voltage of the bias battery, the difference being a few volts negative. An increase in the supply voltage produces some increase in output voltage which raises the grid potential of V_2, thus increasing its anode current and making the grid of V_1 more negative. The result is, therefore, that the greater part of the voltage increase is absorbed by V_1. An increase in the load current reduces the output voltage, thus causing the grid of V_2 to become more negative and, consequently, the grid of V_1 to become more positive. This action gives the stabilizer a good regulation characteristic.

No change in the effective resistance of V_1 can take place until a change has occurred in the output voltage; therefore an increase or a decrease in the supply voltage is necessarily accompanied

* Measurements Section paper.

† College of Technology, Manchester.

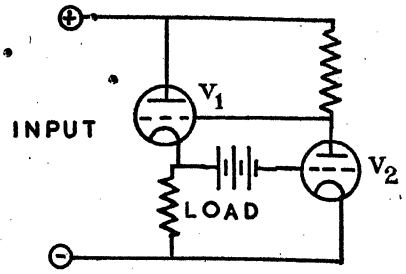


Fig. 1

y a corresponding, but much smaller, change in the output oltage. We may regard the expression $\frac{E}{V} \cdot \frac{dV}{dE}$, where V and E re the input and output voltages respectively, as the figure of ıerit of the stabilizer.

Tests were made with a stabilizer, connected as shown in ig. 1, using valves PX4 and H42. The figure of merit was ound to be 95, and the equivalent internal resistance 5·1 ohms. and E were 230 and 160 volts respectively. This means that the output voltage is not to fluctuate by more than 0·01% the ıpply must be steady to within 1%.

(5) AN IMPROVED CIRCUIT

The circuit shown in Fig. 2 is an elaboration of that of Fig. 1.

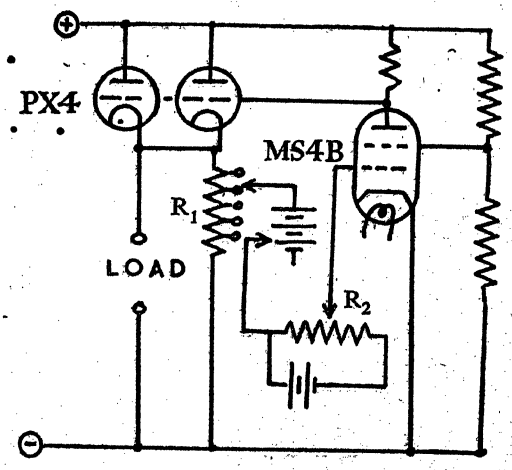


Fig. 2

may be noted that a tetrode, MS4B, is substituted for the ode and that its screen voltage is supplied by a tapped resistor nnected across the input voltage. An increase in the supply ltage therefore raises the screen voltage and consequently in- ases the effective resistance of the PX4 valves. This is a true bilizing action and accounts for the improved result that is tained. Fig. 3 shows the results given by a stabilizer the circuit of which is shown in Fig. 2. It may be noted that the performance improves progressively as the output voltage is raised. For example, when the output voltage is 300 volts and the input voltage is 525 volts, the output voltage is independent of fluctuations of input voltage. With an output of 200 volts, a change of 0·01% is caused by a change of 25 volts in input voltage. The corresponding figure for an output of 100 volts is 4 volts. Therefore, to attain the voltage stability required by the Electricity Commissioners, it is necessary that the source from which the input is obtained shall not fluctuate by more than the amounts indicated. The author has found no difficulty in securing a d.c. supply which fulfils these conditions both when using a motor-generator set and also when using a rectifier unit.

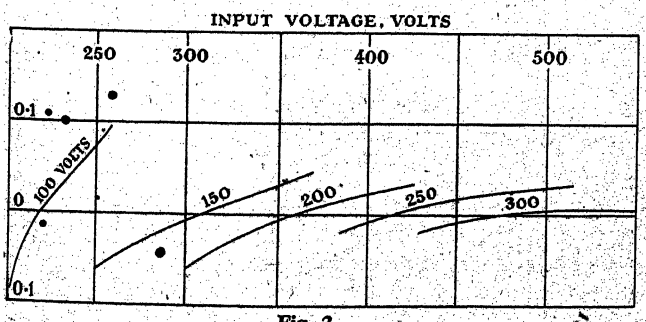


Fig. 3

(6) REGULATION

The curves in Fig. 4 show the effect of load changes on the output voltage for different values of output voltage. The effective internal resistance is about 2·5 ohms and is little affected by the magnitude of the output voltage.

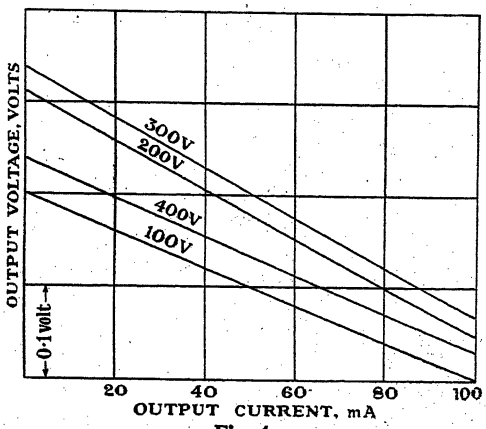


Fig. 4

(7) VOLTAGE CONTROL

Variation of the output voltage may be effected by changing the tapping point on the divider R_1 or by adjustment of the voltage of the bias battery. It has been found convenient to make use of both methods—the first for coarse and the second for fine regulation. The divider R_2 has a resistance of 1·5 megohms and is connected across a 3-volt battery. The battery switch changes the voltage in steps of 1·5 volts. In this way it is possible to control the output voltage smoothly to 1 part in 20 000 and there is no tendency to drift. Since there is no current flowing in the controlling circuit, variable contact resistances do not cause any fluctuation in the output voltage.

(8) POWER OUTPUT

The current which can be supplied by the stabilizer is determined by the type of output valve used. The author uses two PX4 valves, each rated to take 60 mA at 300 volts, in parallel. Since the voltage on the output valves is normally about 150 volts it is thought that a greater current might safely be taken provided that the anode dissipation were kept below the maker's recommended value of 15 watts.

There may be occasions when a much greater stabilizer current is required than can be carried by the output valves. At the cost of a reduced degree of stability, this can be obtained by connecting a suitable resistor in parallel with the output valves, i.e. between the positive input terminal and the valve cathode. This resistor and/or the bias-battery voltage is then adjusted until the anode currents of the power valves are about half the maximum rating.

The author's stabilizer was loaded in this way to provide an output of 0·75 amp at 250 volts when the input voltage was 400 volts. It was found that a 4-volt change in the input caused a 0·1-volt change in the output. This is equivalent to a figure of merit of 25.

(9) ELIMINATION OF VOLTAGE RIPPLE

Although the presence of a ripple on the voltage supplied to the voltage circuit of a wattmeter or to a voltmeter under test does not, in theory, affect the result, it can produce a blurring of the galvanometer spot. Whether the input voltage is obtained from a motor generator or from a rectifier, it may be expected to have a superimposed ripple of a few volts. An investigation with the cathode-ray oscillograph has shown that this ripple is almost entirely eliminated by the stabilizer. Oscillographic records of the ripples on the input and output voltage waves of the stabilizer when supplied with current from a valve rectifier are shown in Fig. 5. The load was 80 mA at 200 volts. It may

Fig. 5

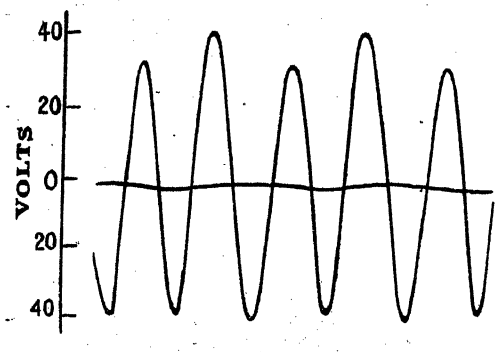
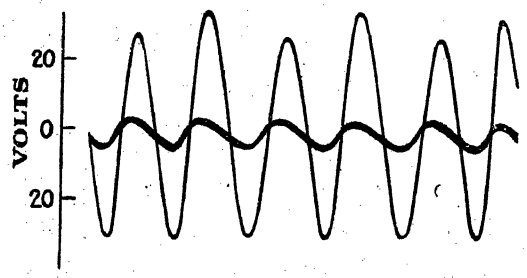


Fig. 6



be noted that the residual alternating voltage on the output is at a frequency of 50 c/s and therefore probably comes from the valve-cathode heating supply.

(10) OTHER D.C. STABILIZERS

As far as the author is aware, the only apparatus which has been marketed as a substitute for the H.T. battery in meter testing stations consists of a motor-generator set in which the generator field is controlled by means of valves. This device does not appear to have enjoyed much success.

The need for stabilized d.c. voltage supplies has been felt in various branches of radio work, and there are several methods available for providing such supplies. Some of these were tried by the author, but he failed to obtain a voltage sufficiently stable to satisfy the requirements of the Commissioners.

A stabilizer has been described* which in some respects resembles the author's; according to the published description of the device, however, the stability is such that to obtain a voltage constant to within 1 part in 10 000 would require an input voltage which did not fluctuate by more than 0·2%.

Another device for providing a steady voltage depends on the constant voltage-drop between the electrodes of a neon-filled tube.* This is about 70 volts, and the output of the apparatus is therefore some multiple of that value. The author made some tests on this device and found that when it was supplied with a perfectly steady voltage the output fluctuated by more than 1 part in 10 000. Further, during the first half hour the output changed by some 1%. Fig. 6 shows an oscillographic record of the ripple voltages on the input and output of the device when supplied from the same valve rectifier as was used to obtain the record of Fig. 5. The load was 60 mA at 210 volts.

* *Amateur Radio Handbook*, 2nd ed., p. 157.

(11) APPLICATIONS

(11.1) General

The stabilizer has been developed mainly for the purpose of standardizing wattmeters and voltmeters, but the author believes that it will be found useful for supplying experimental furnaces and for work with photocells which require a light source of very constant candle-power. The manufacturers of moving-coil instruments may well find that it can provide a voltage for calibrating these instruments which is more constant and convenient than that derived from batteries.

(11.2) Use of the Stabilizer in Standardizing the A.C. Potentiometer

The author uses the stabilizer to provide the direct current required for standardizing the a.c. potentiometer. It may be recalled that, when using the co-ordinate a.c. potentiometer, it is necessary first to pass a direct current of 50 mA through the "in-phase" slide-wire and to adjust this current to its proper value by means of a standard cell. The usual practice is to use four 2-volt accumulators to provide the current. Therefore each time the dynamometer is re-checked it is necessary to alter the setting of the rheostat and to wait until the current becomes constant. By using the stabilizer to provide the current these difficulties are avoided. The "in-phase" slide-wire circuit is connected in series with a resistance of about 2 000 ohms to the stabilizer, the voltage of which is adjusted until the required current is obtained. If a shunt which gives a voltage drop of 1·0183 volts (the voltage of the standard cadmium cell) with a current of 50 mA is included in the circuit the re-checking of the dynamometer is greatly facilitated.

(11.3) Use of the Stabilizer in Checking the Accuracy of the D.C. Potentiometer

The stabilizer provides a very convenient supply for checking the equality of the resistances of the sections of the potentiometer. The procedure used by the author for testing a Tinsley vernier potentiometer will be detailed, but the method may easily be adapted to suit other makes of d.c. potentiometer. The Tinsley instrument is fitted with three dials: No. 1 reads 0·1 volt per division; No. 2, 1 millivolt per division; and No. 3, 10 microvolts per division.

The only apparatus required, in addition to the stabilizer, is a potential divider which can provide ratios of approximately 2 000 : 1, 2 000 : 2, etc. This may conveniently consist of a 10 000-ohm resistor in series with two 50-ohm resistors, the first being tapped at every fifth ohm. The exact values are not important.

The first part of the operation is to compare the voltage drop in each of the sections in dial No. 1 with that in 100 divisions of dial No. 2. The potential divider is set to give a ratio of 2 000 : 1 and is supplied with a voltage of about 200 volts from the stabilizer, the output being approximately 0·1 volt. This output is connected to the potentiometer, which is set to read:

* "The Marconi Stabilovolt Current Supply System," *Marconi Review*, 1933, No. 44, p. 22; and 1933, No. 45, p. 12.

No. 1, 1; No. 2, 0; No. 3, 50. A balance is obtained by adjustment of the stabilizer voltage control, and the potentiometer setting is then altered to: No. 1, 0; No. 2, 100; and No. 3 is adjusted to balance. The movement of No. 3 is then a measure of the difference between the voltage drop in the first section of No. 1 and that in 100 divisions of No. 2. The potential-divider ratio is changed to 2 000 : 2 and the operation repeated for the second section; and so on. If the balance can be obtained to the nearest stud on dial No. 3, the error in measurement should not exceed 5 microvolts.

The voltage of each section of dial No. 2 is compared with that in 100 divisions of dial No. 3. The potentiometer is set to read: No. 1, 5; No. 2, 1; No. 3, 0·02; and the divider and stabilizer are adjusted to balance. Dial No. 2 is then set to 0 and No. 3 adjusted to balance. This measures the voltage in the first section of dial No. 2 on No. 3. The procedure is repeated for all sections.

In most cases the above will be regarded as a sufficient check, but a further test on dial No. 3 can be made, if required, by comparing the drop in one section of dial No. 2, when the range-reducing plug is in the 0·1 position, with that in 10 sections of No. 3 with the plug in its normal position.

The Electricity Supply (Meters) Act requires that the standard potentiometer shall not be in error by more than 0·0002 volt at any point; one division of dial No. 3 corresponds to 0·00001 volt. The stabilizer has been found to provide a voltage sufficiently steady to enable measurements to be made to this degree of precision.

PAPER No. 2: THE USE OF A SIMPLE A.C. POTENTIOMETER FOR THE PRECISION TESTING OF INSTRUMENT TRANSFORMERS

SUMMARY

The paper opens with a description of a simple form of co-ordinate a.c. potentiometer which requires little power to operate and is very light and portable. Its application to the measurement of the ratio and phase errors of a voltage-transformer follows. It may also be used to measure the errors of current-transformers, and several methods are described which avoid the difficulties inherent in the more usual "spill current" methods. Brief notes of the construction of an oil-cooled, shielded resistor for 33 kV, and of two standard current-transformers, are given.

(1) INTRODUCTION

The co-ordinate form of the a.c. potentiometer is probably the most flexible and adaptable instrument for making measurements of current, voltage and power at commercial frequency. It can be used to measure currents ranging in magnitude from microamperes to thousands of amperes, voltages from millivolts to kilovolts, and corresponding ranges of power. High accuracy can be obtained by using the precision form of the instrument in conjunction with stabilized voltages, as described in a previous paper.[1] But for many purposes this degree of accuracy is unnecessary and it is possible to employ a form of potentiometer which is more convenient and portable than the somewhat elaborate equipment required for the highest accuracy. The simplified potentiometer can then be regarded as a sub-standard whose accuracy can be verified from time to time by means of the precision instrument.

Some time ago, an oil-cooled and shielded resistance voltage divider was constructed with a view to the calibration of voltage transformers. It became necessary to find some means of measuring the difference between the secondary voltage of the transformer under test and that of the low-voltage section of the divider. Accordingly, a simple form of potentiometer was designed and constructed, the input being taken from the secondary of the transformer under test, which directly measures the ratio error and phase angle of the transformer.

It was found later that the same instrument could be used to measure, very conveniently, the ratio error and phase angle of a current transformer. This fact, then, is the author's justification for describing the two measurements in one paper.

(2) DESIGN OF THE SIMPLE POTENTIOMETER

The specification to which the potentiometer was designed may be stated as follows:

(*a*) A minimum of power should be required to operate it, because this would form a burden on a voltage transformer under test.

(*b*) The output voltage to be read directly as a percentage of the input.

(*c*) The standard input voltage to be 110 volts at 50 c/s.

(*d*) The current in the "in-phase" slide-wire to be in phase with the input voltage.

(*e*) An accuracy of 1%.

Fig. 1 shows the circuit of the instrument as finally constructed.

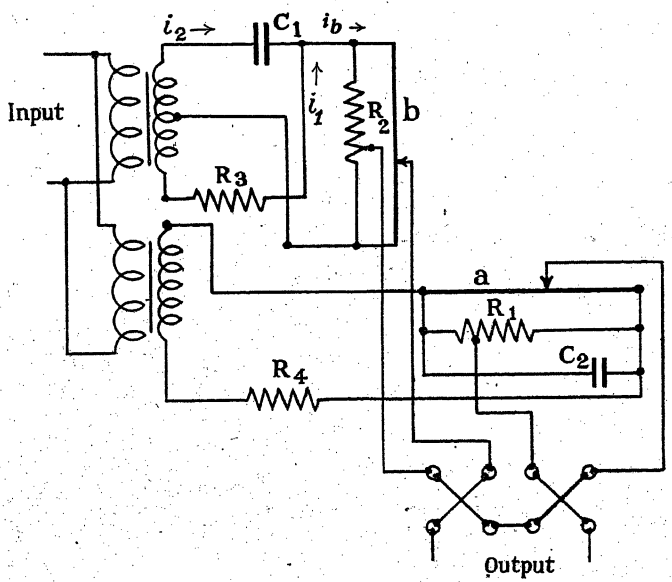


Fig. 1

The apparatus is fitted into a box measuring 10 in × 5 in × 5 in and is built of radio components, some of which had to be modified for the purpose. The "in-phase" slide-wire "a," and the "quadrature" slide-wire "b," are each fitted with a "false" zero which permits a small negative reading to be observed. The slide-wires are 50-ohm voltage dividers mounted on porcelain bases, and the dials on which movements of the contacts are indicated are divided into 100 divisions, each of which represents 0·01% of the input voltage.

The condenser C_2 serves to adjust the current in the slide-wire "a" to phase coincidence with the input voltage. The necessary adjustments of the resistors R_1, R_2, R_3 and R_4 were made, once for all, with the assistance of the precision potentiometer. It was found possible to arrange that the leading current taken by the condensers should almost neutralize the magnetizing current

of the transformers, so that the total input current was very nearly in phase with the voltage. At 110 volts this current is about 5 mA, corresponding to a burden of approximately 0·5 VA. The accuracy of the instrument is about 1%, and at 50 c/s the voltages on the slide-wires are in quadrature to within 15 min.

Fig. 2 is a vector diagram which shows how quadrature between the slide-wire currents is obtained.

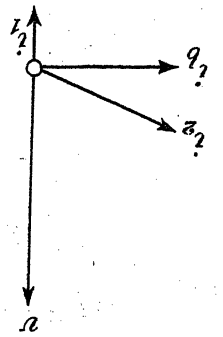


Fig. 2

(3) APPLICATION OF THE POTENTIOMETER TO THE TESTING OF VOLTAGE TRANSFORMERS

The ratio and phase angle of a voltage transformer may be measured either by comparison with a calibrated transformer having the same nominal ratio or by means of a voltage divider. The first method requires the use of a sub-standard, calibrated by some outside authority, but the second is an "absolute" method because the true ratio of the voltage divider can be found by the user.

Fig. 3A gives the circuit used for measuring the ratio and phase-

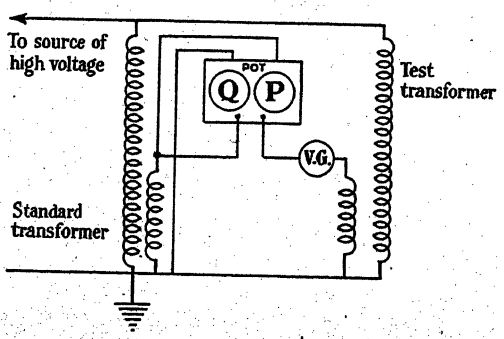


Fig. 3A

angle differences between a transformer under test and a standard. The potentiometer dials are adjusted until the vibration galvanometer is balanced; the dials then indicate the ratio and phase-angle differences, the scales being, respectively, 0·01% and 0·0001 radian per division. The standard transformer should be calibrated with the potentiometer as a burden, although it is unlikely that so small a burden would appreciably affect the result.

The construction of a standard high-voltage resistance voltage divider has been described elsewhere,[2] and therefore only a brief account of the apparatus used by the author need be given here.

It consists of a main and a shield resistor connected in parallel with the high-voltage supply, the former designed to take a current of 50 mA and the latter 20 mA. The resistors are contained in a number of oil-filled, rectangular steel tanks—2 000 volts to each. Each tank is maintained at the average potential of the section of the main resistor which it contains by being connected to the mid-point of the corresponding section of the shield. The main resistor, therefore, is so screened that the maximum voltage between any point and the containing tank is 1 000 volts. The final 2 000 ohms at the earthed end is tapped to form the low-voltage section.

A number of tests at 50 c/s have been made on this resist and they indicate that the phase angle between the voltage on t low-voltage section and the terminal voltage does not exce 0·2 min.

The circuit used for measuring the ratio and phase angle a voltage transformer by means of the voltage divider is shov in Fig. 3B. The potentiometer forms a burden on the trar

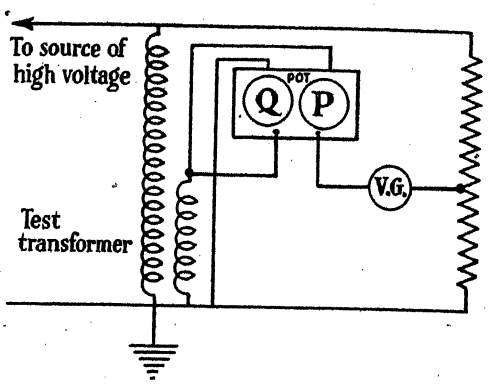


Fig. 3B

former, the effect of which can be estimated by observing th changes caused by an additional burden of 0·5 VA, i.e. a resis tance of 20 000 ohms.

Some tests were made on a 12 000-volt transformer to show th consistency of the results obtained by the method describe above. In Fig. 4 the ratio and phase errors with various burden

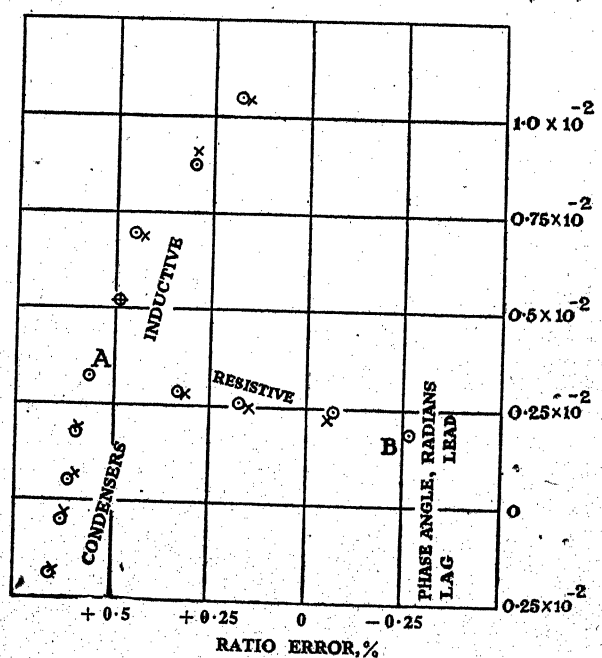


Fig. 4.—Test on voltage transformer.
Ratio 12 000/100. Tested at 12 000 volts. Point A at zero burden.
Point B at 200 VA. Points marked × calculated from A and B.

(resistive, capacitive and inductive) are shown. The errors for the same burdens have been calculated on the assumption that the observed errors at zero and at 200 VA (resistive) are correct, and the calculated values are indicated in the Figure for comparison with the observed points. The agreement is good in all cases.

(4) CURRENT-TRANSFORMER TESTING

Current transformers are usually tested by comparison with a calibrated standard having the same nominal ratio as that of the transformer under test. One of the best known methods is the Arnold bridge, which was described[3] and discussed at a meeting of the Meter and Instrument Section in 1933. The principle of the bridge is shown in Fig. 5; here R is a resistor through which

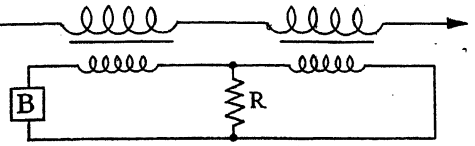


Fig. 5

the difference or "spill" current passes, and the voltage drop in R is measured by means of a form of potentiometer. With the bridge as described in Arnold's paper, the maximum voltages, in phase and in quadrature, which can be thus measured are only 2·5 millivolts. This voltage is so small that stray e.m.f.'s can vitiate the result, and elaborate precautions must be taken to avoid this. Very accurate results can be obtained when the apparatus is in the hands of an expert observer, working under favourable conditions.

The method shown in Fig. 6A was introduced by Nölke[4] in 1938. The current from the phase shifter is adjusted in magnitude and phase until the vibration galvanometer is balanced; the ratio of the currents i_1 and i_2 and the angle between their vectors are then measured and the errors calculated. The outstanding features of this method are: (*a*) The balance is very critical and

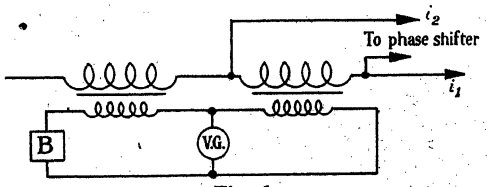


Fig. 6A

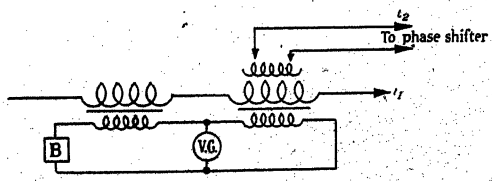


Fig. 6B

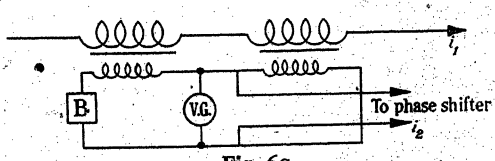


Fig. 6C

is almost unaffected by stray fields. (*b*) There is no limit to the power available for making the current measurements. (*c*) No burden is imposed on the transformers by the test circuit, and the standard can therefore be used with zero burden, a condition in which it has a minimum error.

Figs. 6B and 6C* show variations of Nölke's method; in the arrangement of Fig. 6B the phase shifter (or "compensating") current is passed through a tapped tertiary winding on the standard and it is therefore possible to match the magnitude of the compensating current to the means available for its measurement. In Fig. 6C the compensating current circulates in the secondary windings and is evidently equal to the "spill" current which would be measured by Arnold's method. In all three methods the presence of stray fields affects the result very little.

If speed of calibration is of paramount importance, as when large numbers of identical transformers have to be tested after manufacture, direct-reading instruments for measuring the currents are advantageous; but the author has found that the simple potentiometer provides a convenient and sufficiently rapid method of current measurement when only one or two transformers have to be tested. The voltage drops in suitable shunts are measured by the potentiometer and, since it is only the ratio between the currents that is required, the exact value of the input voltage to the potentiometer is not important. It is desirable, for convenience in the subsequent calculation of results, to arrange that the phase of one of the currents should coincide with that of the current in the "in-phase" slide-wire. In the circuit used by the author (Fig. 7) the potentiometer is supplied from the secondary

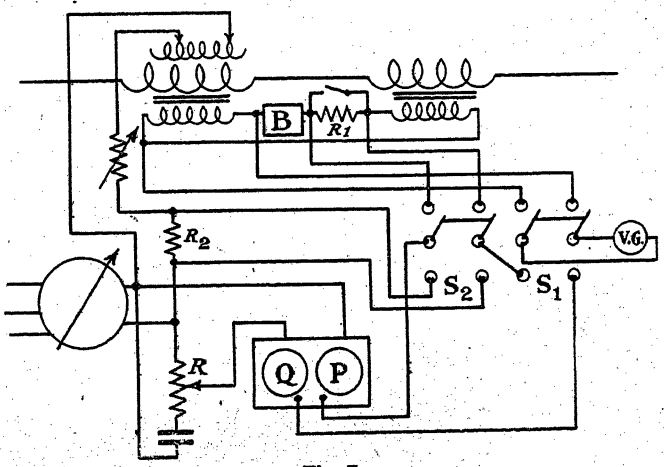


Fig. 7

of the phase shifter and a small amount of phase adjustment is provided by the divider R. Suitable switches mounted on a small switchboard permit the readings to be rapidly made.

The following three observations have to be made for each calibration:

(i) With the switch S_1 in the upper position and R_1 short-circuited, adjust the compensating current until the vibration galvanometer is balanced.

(ii) With S_1 and S_2 in the lower positions, and the quadrature dial (Q) at 0, balance the galvanometer by means of the in-phase dial P and the phase adjuster. Note the reading (x).

(iii) The short-circuit is removed from R_1, S_2 is moved to the upper position and a new balance is obtained by adjustment of both dials. Let the reading be $a + jb$. If the numbers of turns on the secondary and tertiary windings are N_1 and N_2 respectively, we have

$$\text{Ratio difference} = \frac{xa}{a^2 + b^2} \times \frac{N_2}{N_1} \times \frac{R_1}{R_2}$$

$$\text{Phase difference} = \frac{xb}{a^2 + b^2} \times \frac{N_2}{N_1} \times \frac{R_1}{R_2} \text{ radians}$$

Ample accuracy in the calculation of the results may be obtained with a slide-rule. When high-ratio current transformers are being tested the primary current is usually obtained from the low-voltage secondary winding of a transformer. The power factor of the heavy-current circuit is therefore low and it would be inconvenient to adjust the phase of the input to the potentiometer to coincide with that of the current, although if this were done the

* The author's attention has been drawn to the following article by G. W. Stubbings, in which the principle of the method of Fig. 6C is described: "Testing Current Transformers," *Electrical Review*, 1933, 112, p. 480.

calculation would be still further simplified. With low-ratio current transformers the primary current can be kept nearly in phase with the supply voltage, and it may therefore be used as the input voltage to the potentiometer. The compensating current will then be measured as two components, one being proportional to the ratio error and the other to the phase angle.

An experiment made to show the critical nature of the balance obtained by this method may be cited. The standard current transformer described later in this paper, with a ratio of 10/5, was connected to another transformer with the same nominal ratio, as shown in Fig. 6B. A balance on full load was obtained by adjustment of the compensating current. The compensating ampere-turns were then increased by 0·01% of the secondary ampere-turns, and the resulting e.m.f. in the galvanometer circuit, measured on the potentiometer, was found to be 70 millivolts.

(5) THE STANDARD TRANSFORMER

The methods of testing which have been discussed require standard transformers with the same nominal ratios as the transformers under test. The procedure is to construct a transformer, with a 5/5 ratio, whose primary winding can be rearranged without alteration to the errors, to provide other ratios. The standard used at the National Physical Laboratory and described in Arnold's paper is heavy, weighing some 1·5 cwt, and it was decided to construct one which would be much lighter. Since the new standard would be used with zero burden it was hoped that its errors would not greatly exceed those found for the N.P.L. standard.

The core is of Mumetal, 10 cm outside diameter, 8 cm inside diameter and 7·5 cm long. The secondary has 200 turns of 7/·036 d.c.c. wire with a resistance of 0·183 ohm. The primary winding consists of 10 turns of a 20-core cable (No. 17 S.W.G.) and the 20 cores are connected to switches which admit of their being connected in series, series-parallel or parallel. The following ratios are available: 5/5, 10/5, 20/5, 25/5, 50/5 and 100/5. A tertiary winding of 110 turns is so connected to two 11-contact switches that any number of turns may be used. The weight, with case, is 33 lb.

(6) CALIBRATION OF THE STANDARD TRANSFORMER

The transformer referred to in the previous Section was calibrated on its 5/5 ratio by a modification of a method, described elsewhere,[5] which is shown in principle in Fig. 8. The compensating and primary currents were measured, after the galvanometer had been balanced, by means of the potentiometer. The results of a recent calibration are given in the Table. They were found to have changed by less than 1 part in 100 000 during a period of 4 years. At full load the ratio error is 13 parts in 100 000 and the phase-angle error is 0·49 min. The corresponding errors in the N.P.L. standard are 2 parts in 100 000 and 0·44 min.

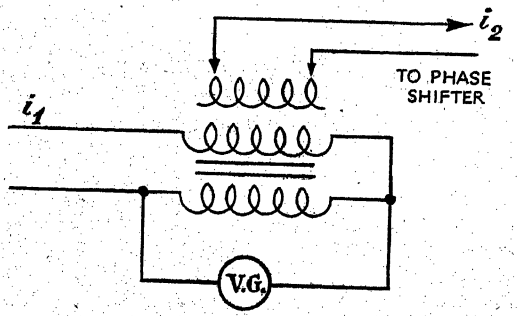


Fig. 8

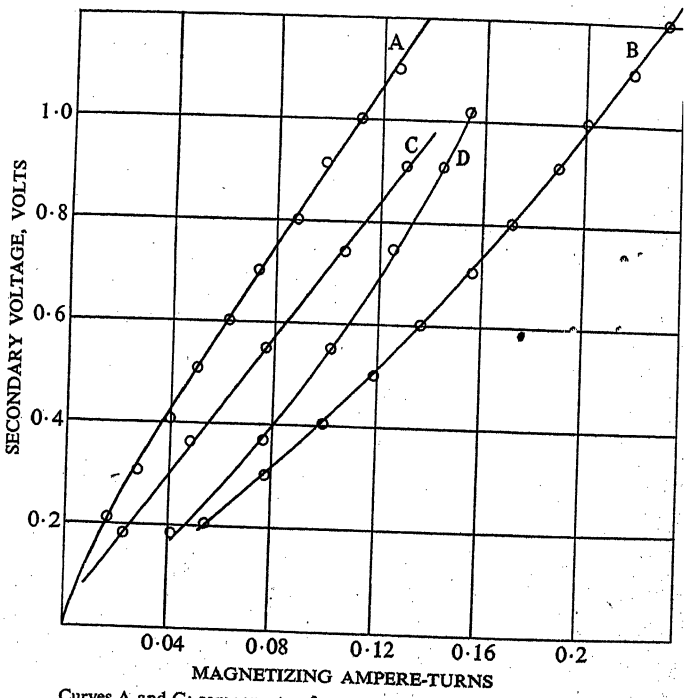
Table

CALIBRATION OF STANDARD TRANSFORMER, RATIO 5/5

Burden: zero

Current	Ratio error	Phase angle
amp	%	min
5	$0·013_4$	0·49
4	$0·013_4$	0·54
3	$0·013_1$	0·60
2	$0·012_5$	0·67
1	$0·012_0$	0·75

With a view to confirming the calibration of the standard, th relation between the ampere-turns applied to the transforme and the e.m.f. developed in the secondary winding was measure by means of the potentiometer, and the results are shown by th curves A and B in Fig. 9. On the assumption that the impedanc



Curves A and C: components of ampere-turns in phase with voltage.
Curves B and D: components of ampere-turns in quadrature with voltage.

Fig. 9

of the secondary winding is purely resistive, the components of the exciting ampere-turns for a given secondary e.m.f. can be deduced from the calibration of the transformer. These are plotted in the curves C and D. It may be noted that the in-phase component calculated in this way is greater than the observed value and that the quadrature component is less. The difference between the results given by the two methods of measuring the errors is about 3 parts in 100 000. If, however, the impedance of the secondary winding is assumed to have a phase angle of about 15° the observed and calculated results are in agreement within 1 part in 100 000.

The following tests were made to justify the assumption that the errors on all ranges are the same.

(*a*) A resistance of 1 ohm was connected between two of the coils in the primary winding and the errors were measured at full load. If any of the primary current were shunted from coil

to coil either by conductance or by capacitance, the errors would thereby be altered. (No change could be detected.)

(*b*) If, when the coils are connected in parallel, the current distribution is non-uniform and if the coils do not all produce the same m.m.f. on the core, there will be an error. This point was investigated by comparing the transformer on its 100/5 ratio with another having the same ratio and open-circuiting each coil in turn. (No alteration of balance could be detected.)

(7) THE SUB-STANDARD TRANSFORMER

The primary standard transformer provides the more common ratios up to 100/5, but, since current transformers with higher ratios have frequently to be calibrated, a sub-standard of the inserted primary type has been constructed. This instrument has a Mumetal core and is provided with a secondary, the number of whose turns can be selected. The secondary is wound in seven sections, the turns on each section being equally spaced and the ends brought out to terminals on the case. The numbers of turns on the sections are: 100, 100, 40, 30, 20, 10 and 5; it is therefore possible to obtain ratios up to 1500/5.

The transformer was calibrated in steps of 100 amp from 500/5 to 1500/5, i.e. using a secondary winding the number of whose turns increased by steps of 20 from 100 to 300. A cable carrying a full-load current of 100 amp was threaded through the central hole an appropriate number of times for each test. The primary current was then passed through the 100/5 primary standard and the errors measured as described. If all turns were of the same resistance the errors with zero burden should be inversely proportional to the number of secondary turns in use. This is evident, because the e.m.f. per turn required to maintain a given secondary current is independent of the number of turns; and hence the core flux, and the ampere-turns which produce it, must be constant. The error is given by

$$\frac{\text{Magnetizing ampere-turns}}{\text{Secondary current} \times \text{Secondary turns}}$$

and the proposition follows.

(9) CURRENT-TRANSFORMER CALIBRATION BY MEANS OF A "MIXER" RING

G. F. Freeman[6] has described a direct method for the calibration of a current transformer the ratio of which is not unity. The principle of the method is shown in Fig. 10. The Mumetal

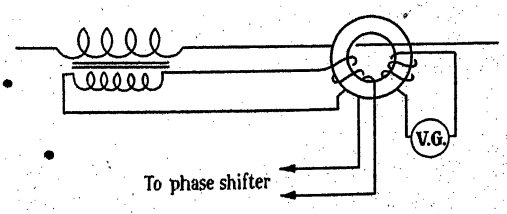


Fig. 10

"mixer" ring is wound with a turns ratio equal to the nominal ratio of the transformer, and the compensating current is adjusted to balance the vibration galvanometer. The transformer errors are then given by the ratio (Compensating ampere-turns)/(Ampere-turns on ring). At balance, there is no flux in the ring and the burden imposed on the transformer is therefore only the resistance of the mixer ring winding. With low-ratio transformers the burden is small, but if a high-ratio transformer (say 1000/5) is tested by this method the burden is considerable. Freeman suggests an accuracy of about 0·1%, but the author has been able to obtain considerably better results than this when using a modification of his method in which the currents are measured on the potentiometer.

(10) THE COMPARISON OF FOUR-TERMINAL RESISTANCE STANDARDS

A testing laboratory is usually equipped with a number of resistance standards, having nominal ratios of 1, 0·1, 0·01 ohm, etc., for measuring currents by means of the d.c. potentiometer. These are the primary standards of the laboratory and must be re-checked at intervals by a standardizing authority. Occasionally the resistance of one of these standards may change and this may cause serious errors. The primary standard current transformer provides a very convenient means of measuring the ratio between the a.c. resistances of the standards. This ratio may not be quite the same as the ratio of the d.c. resistances, but any change in its value gives an immediate warning of a change in the resistance of one of the standards.

The method used will be explained by detailing the procedure for comparing the resistances of two standard shunts whose nominal values are 0·1 and 0·01 ohm. The connections are as shown in Fig. 11. A current of 10 amp is passed through the

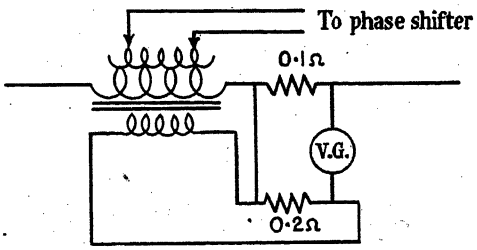


Fig. 11

0·1-ohm shunt in series with the primary of the transformer, which is arranged to have a ratio of 10/5. A 0·2-ohm shunt is connected in the secondary circuit. The compensating current is adjusted to give a balance, and the currents are measured on the potentiometer. The 0·01-ohm shunt is substituted for the 0·1-ohm, the ratio is changed to 100/5 and the measurement repeated with a primary current of 100 amp. The difference between the in-phase components of the compensating ampere-turns in the two experiments is a measure of the percentage difference between the departures of the shunt resistances from their nominal values. The differences between the quadrature components is a measure of the difference between the phase angles of the shunts. An accuracy of 1 part in 100 000 can be obtained when comparing shunts of equal nominal values; for example, the changes due to temperature in the resistance of a manganin shunt can be conveniently measured.

It will be found that a vibration galvanometer of considerably greater sensitivity than need be used for the transformer testing must be employed when making this measurement.

(11) REFERENCES

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(2) R. DAVIS: "The Design and Construction of a Shielded Resistor for High Voltages," *ibid.*, 1931, **69**, p. 1028.

(3) A. H. M. ARNOLD: "Current-transformer Testing," *ibid.*, 1934, **74**, p. 424.

(4) O. E. NÖLKE: "Messwandler-Prüfeinrichtung nach dem Differential-Nullverfahren," *Elektrotechnische Zeitschrift*, 1938, **59**, p. 41.

(5) A. GLYNNE: "Instrument Current Transformers," *Electrician*, 1939, **122**, p. 341.

(6) G. F. FREEMAN: "Current-transformer Errors," *Electrical Review*, 1939, **125**, p. 756.

DISCUSSION BEFORE THE MEASUREMENTS SECTION, 21ST JANUARY, 1944

Dr. G. F. Tagg: The first paper is another example of the application of thermionic devices in testing equipment. A comparable degree of control of 1 in 10 000 has not even been approached by any electromechanical device.

The author says, in connection with the source of the d.c. input, that self-excitation would not be suitable for a d.c. machine; I cannot see why the machine should have to be separately excited.

Also, he says that the only other similar apparatus of which he is aware is a device in which a motor-generator set is controlled by valves. For some years I have used circuits in which the field current of motor-generator sets has been controlled by valves, and this has given a degree of stability of 1 in 10 000 without much difficulty. The system has the advantage that the output is limited only by the output of the machine; with a 6-kW machine under such control any load up to 6 kW can be obtained at the stabilized voltage.

The circuit of a stabilizer I use for a 200-volt machine consists essentially of a d.c. amplifier connected to the armature of the machine through a potential divider. Variations in the armature voltage are used to control the grid bias of the first valve of the amplifier, and, through the amplifier, to control the grids of a large bank of triode valves. These valves are in series with the field winding, and in effect form part of the field resistance.

This arrangement can be regarded either as a variable resistance or as a source of current. The supply for the field of the machine was actually taken from the a.c. mains through a valve rectifier and smoother. With the arrangement, the output voltage of the machine remains constant within 1 in 10 000 during the whole day when the machine is left running, and between no load and a load on the generator as represented by a fairly large motor-alternator set, since the stabilized direct current can also be used to drive the motor of a motor-alternator and to provide the field current of the alternator, thus making it possible to get a steady a.c. supply as well.

The amplifier section of the equipment has two pentode amplifiers in the centre; the triodes are placed round them. The rectifier section contains the rectifying valve supplying the field current to the generator and the rectifying valve feeding power to the d.c. amplifier.

I have had these sets working on generators with outputs varying from 200 to 600 volts, and also on loads varying up to about 6 kW. The d.c. supply from them has been used successfully for the potential testing of wattmeters, voltmeters and other instruments. In a test run yesterday to make sure that conditions were absolutely steady, the machine was left running from 8 a.m. to 5.30 p.m., and the change was less than 1 in 10 000 during the whole of that time.

On reading the second paper, it occurred to me that the small a.c. potentiometer might have a number of other useful applications, particularly in the testing of materials, such as the magnetic properties of iron, as the high degree of accuracy obtainable with a precision a.c. potentiometer is not necessary, and a quick and reasonably accurate method of measurement is all that is required. In view of this, I should appreciate a more detailed description of the potentiometer.

Mr F. L. Hogg: Surely the author's first paper could be more appropriately called "The Application of an Electronic Stabilizer to the Testing of Electricity Meters." Fig. 1 is conventional, dating back at least ten years. In the text the author does not specifically claim any novelties. Much has been published on electronic voltage stabilization; the classical paper being that of Hunt and Hickman.* The literature shows prior publication of all design points raised by the author.

* *Review of Scientific Instruments*, 1939, 10, p. 6.

In Section 4 of the first paper, the author includes the factor E/V in the figure of merit of the stabilizer. This factor is a function of the operating conditions, and not of the stabilizer as such. The conventional method of rating is by the stabilization ratio $\delta E/\delta V$ with i constant, while the other parameter, the internal resistance, is $\delta E/\delta i$, with V constant. Has the author any reason for departing from this convention?

The effect of screen compensation, which the author describes in his improved circuit, Fig. 2, is well known, but no complete theoretical investigation of the circuit has apparently been published. The author does not give any circuit values or any indication of the way in which the screen-voltage potentiometer affects the result. [Mr. Hogg exhibited a curve just received from a correspondent at the Selo Physics Laboratories which showed the marked changes in performance of this form of circuit resulting from a variation of the screen voltage.]

The operation of this particular circuit depends very much on the valve which is used. In a 300-volt stabilizer with a 9D2 variable-mu pentode as control valve which I once used, a very high degree of stabilization was obtained over a very wide range by extremely critical adjustment of the screen voltage, but a very small variation in screen voltage led to over-compensation. On changing to an 8D2 sharp-cut-off pentode the compensation almost entirely disappeared. The mutual conductance of the screen to other electrodes is apparently the controlling factor.

In nearly all practical cases, much better regulation is obtained if the anode resistance of the MS4B in Fig. 2 is connected to the cathode instead of to the anode of the PX4's. The theoretical improvement is approximately μ times, but is slightly offset by a fall in volts on the MS4B anode.

Fig. 5 shows a very high residual ripple of about 2 volts; possibly this is due to the absence of a centre tap on the PX4 filaments in Fig. 2. A mediocre regulator usually leaves the ripple about 70 db down, and a good one will easily exceed 80 db, which would not be visible on the curve in Fig. 5.

The author's short-term stability figures are very optimistic, unless extreme care is taken. Small variations in emission and in resistances produce quite large effects.

Mr. A. Hobson: A potentiometer to be used for all kinds of voltage transformer should have a ratio range of $\pm 2\%$, and about the same phase-angle ratio, namely $\pm 2\%$ radian. Preferably it should also have two ranges, to ensure good readings with the higher-accuracy transformers. The range of the author's instrument in the second paper seems to be about 1% in one direction and only about 0·1% or 0·2% in the other. It would be difficult to provide a second range on this equipment because the circuit constants would be upset.

I do not agree with the author on the advantages of the Nölke method, although it can be made more sensitive than the Arnold method. The main difficulty in the method is that the phase difference between the primary current and the neutralizing current must be known fairly accurately. To take full avail of the extra sensitivity, this phase difference must be known within about 5 min. This may be reasonably simple for low primary currents, because both currents may then be taken directly from the same supply, but is extremely difficult when a current-supply transformer is used, the normal case in practice.

The author has shown very great ingenuity in using his potentiometer for testing current transformers, for which it was not designed. It is a pity that the method has rather a limited practical use. Compared with Dr. Arnold's set it is most complicated to work; the bridge has to be balanced three times and then the errors worked out by slide-rule. No method of changing from plus to minus errors is given.

I think the resistor R_1 in Fig. 7 is undesirable, especially if it is on the test-transformer side. The range of the potentiometer is about 1 volt, so that R_1 may be about 0·2 ohm. If that is so the transformer cannot be tested at less than 5-VA burden. It seems preferable to put R_1 in the standard transformer secondary, which would not affect the results very much, although it would nullify the author's claim that the standard was working on zero burden.

Mr. S. N. Pocock: I disagree with the author's statement that the effect of screen compensation is a true stabilizing action. Actually the application of that compensation does not necessarily improve the stability, and it may move the regulation characteristic into the negative direction. I have obtained much better and more predictable results by concentrating on an improvement of the true stabilizing action, by ensuring the maximum gain from the amplifying stage and using a high-slope series valve. Results were very successful using a high-slope pentode as an amplifier; a further advantage of the pentode is that the high gain can be maintained with very low anode voltages; this permits the control of output down to 40 volts or lower.

I see no reason for using a separate battery for the fine control. A fine-control potentiometer can be added as part of the control network to give a constant percentage variation.

The residual ripple of the unit may be due to a cause other than the heater ripple on the PX4's. The impedance of the control circuits is rather high and considerable hum pick-up can occur with remote control. This can be cured by a capacitance between the positive end of the load and the MS4B grid, and another capacitance across the output. It enables the ripple output in a typical stabilizer to be reduced to a few hundred microvolts or less.

The author ignores the difficulties sometimes experienced in these stabilizer circuits. Instability is a common cause of trouble, curable by the addition of stopper resistances in grid and anode together with a very small capacitance between the anode and grid of the MS4B in severe cases.

The author has not sufficiently emphasized the great ease of control possible with these units. In many applications it is necessary to set the voltage output to a number of pre-selected values. This can be done very simply using a number of small pre-set potentiometers and switching the MS4B grid to these potentiometers in turn.

Mr. H. D. Hawkes: The basis of all precision measurements is the standard cell and standard resistance, the former with an accuracy of 5 in 100 000 after 24 hours at a constant temperature, and the latter, depending upon its size, with an accuracy of about 5 in 100 000 after a specified time on circuit. It is therefore most gratifying that the author has produced a device which remains constant to 1 in 10 000 indefinitely. A ratio measurement of a few parts in a million as mentioned in Section 6 of the second paper is, however, optimistic, to say the least.

In Section 2 of the second paper the departure from quadrature between the slide-wire voltages is given, but not their relation to the supply voltage, which is even more important.

With regard to voltage-transformer testing in Section 3, I have always been uneasy when testing two voltage transformers of unlike design with a vibration galvanometer as a detector, especially on light load where the exciting-current drop is comparable to or even greater than the load-component drop. Has the author made tests using an aperiodic detector, such as an amplifier and cathode-ray tube, and noted any residual out-of-balance under those conditions? Calculated errors on voltage-transformers always agree remarkably well with observed errors when using vibration galvanometers as detectors, because the harmonic effect due to the exciting current is neglected in both cases. In the same Section the author gives the phase angle of the voltage divider as 0·2 min; is this measurement made at high potential?

In Section 4, the author deals with current-transformer testing; he measures the compensating current and then analyses it. It would seem, advisable, if this is so, for the a.c. equivalent of the author's stabilizer to maintain a constant current during the test. The ideal difference method of measuring current-transformer and voltage-transformer errors is that of Mr. Petch, which was introduced in 1939, and employs the mixer ring.

With regard to the checking of stability of standard resistances by a standard transformer, I should prefer that the standard resistances were used to check the stability of the transformer, for, after all, it is the standard resistance and the standard cell which are the basis of all precision measurements.

Mr. G. F. Freeman (*communicated*): The author's method of self-checking his standard transformer is both ingenious and simple, and has the merit of all differential methods of giving the best results on the best transformers, so long as no stray effects are present.

In the mixer-ring method to which the author refers* the compensating turns were applied to the main transformer instead of the mixer ring, with some advantage in testing miniature precision ring-type transformers; the ampere-turns on the mixer ring are normally only a fraction of those on the main transformer, so that the compensating currents are thus larger and easier to measure. I agree that my estimate of the precision is conservative; over a five-year interval determinations have been found to repeat to within a few parts in 10 000 without difficulty. A nickel-iron mixer ring is, of course, far superior to one of silicon-iron, where the ampere-turns are relatively few.

In the Petch method, for details of which I am indebted to Mr. H. D. Hawkes and which I hope to see more fully described in the *Journal*, the test is indirect, the mixer ring being energized by the spill current between the transformer under test and a standard transformer. There is, therefore, no direct comparison between the two methods.

I feel that the author has made a valuable point in calling attention to the use of Class AL transformers in the checking of standard resistors. It is, of course, a corollary to the use of transformer-resistors by the National Physical Laboratory, but deserves to be more widely realized.

The author gives no details of the use of valve amplifiers in extending the range of cheap vibration galvanometers. I have found this very convenient, providing suitable precautions are taken to avoid strays; a little distortion is of no consequence in view of the frequency selectivity of the galvanometer, but care must be taken with a sensitive galvanometer to avoid switching transients.

Mr. H. S. Petch (*communicated*): I think the author exaggerates the difficulties arising from small-capacity high-voltage secondary batteries. I have had one which has given trouble-free service for five years, but pains were taken to install it carefully to avoid inter-cell leakage. The staffs of the smaller meter test-rooms are more likely to be able to cope with the vagaries of a secondary battery, than to readjust an electronic device following a valve failure, when the performance of the device appears to depend on individual valve characteristics. They will not normally enjoy the author's easy access to superior apparatus.

I endorse the author's high opinion of the simplified co-ordinate potentiometer in Paper 2, but again few have access to a precision instrument for checking. In circuits involving comparison, I think it preferable to take the potentiometer supply from the standard, since the burden is so small; the external burden on the test specimen can then be made substantially zero, which is sometimes essential.

* *Electrical Review*, 1939, 125, p. 756.

I think the author is a little unfair to the Arnold set. Any apparatus sensitive to 2·5 mV is likely to need screening from external fields. The use of a variable mutual inductance certainly make it difficult to use this set in a portable form for site tests.

On the whole, the Nölke method as used by the author appears to have more drawbacks than advantages. It introduces the complication of a double balancing operation, involving highly stable main and compensating supplies, which cannot be easy where heavy currents are concerned, especially in site tests. The apparatus is not direct reading, and requires skilled interpretation of its results. It has switch contacts in continuous use for carrying the secondary currents of both standard and test transformers. The method of connection does not allow the maximum sensitivity of any normal vibration galvanometer to be realized. The standard transformer is complicated by the added tertiary winding, which presumably adds to its size and cost, and to the work of routine checking.

The mixer-ring method referred to in Section 9 is being successfully used in an improved form in testing sets covered by British Patents 527143 and 543748, and overcomes the difficulty of the burden of the winding at heavy current. This burden, in fact, does not exceed 0·1 VA on a transformer with a 5-amp secondary, and is negligibly small on 1- or 0·5-amp secondaries.

Any method of testing voltage transformers which involves earthing a terminal not earthed in service is open to objection. Attention should also be drawn to the necessity for testing a 3-phase voltage transformer on a 3-phase supply, although a single-phase standard may be used.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. A. Glynne (*in reply*): My object in designing the stabilizer described in the first paper was, first, to provide a substitute for the high-tension battery usually required for instrument testing and, secondly, to show that such a stabilizer was suitable for use in meter-testing rooms. Since no evidence has been given to indicate that apparatus of this kind is in use at any of the meter-testing stations established under the Electricity (Meters) Act 1936, the device can fairly be described as new.

In reply to Dr. Tagg: If the stabilizer output is to be from 650 to 100 volts, the input should be adjustable between approximately 800 and 200 volts. It would be difficult to obtain a self-excited generator capable of supplying this wide variation of voltage. I agree that if much power is required a motor-generator set with valve-controlled field current has advantages, but for the present purpose only a very limited current is needed and this can be supplied by purely static apparatus. Motor-generator sets similar to that described by Dr. Tagg are on the market, but do not appear to have been employed in meter-testing rooms, and it is very doubtful whether one could be designed to have the smooth and precise control of voltage achieved by my stabilizer.

In reply to Mr. Hogg: Fig. 1 was included to explain the principle. I consider that the stabilizer ratio $\delta V/\delta E$ gives a too optimistic valuation of the stabilizer performance. The ratio used in the paper is (percentage voltage change in input)/(percentage voltage change in output). A resistance voltage-divider, which has no stabilizing power, would when measured in this way give a figure of unity, but if measured by the method quoted would give a figure of merit equal to the ratio of division. The resistances are not very critical, nor does a change of valve affect the performance. The anode resistance of the MS4B is 200 000 ohms and the screen divider ratio is 100 000/20 000. I connected the anode resistance as suggested, but found that stabilization was reduced and that the effective internal resistance was increased some ten times.

In reply to Mr. Hobson: The potentiometer shown at the meeting was fitted with two reversing switches, as shown in Fig. 1, which give it ranges of $\pm 1{\cdot}3\%$ and $\pm 1{\cdot}3$ centiradians for phase angle. So far this has proved adequate. I did not think it desirable to complicate the instrument by additional ranges, but the same arrangement as fitted to other potentiometers could be used. I do not understand how Mr. Hobson arrives at his figure of 5 min. The instrument measures the angle between the vectors of the secondary and compensating currents with an accuracy of 30 min. The resulting accuracy in the determination of the ratio of a current transformer with an error of 1% is 1 part in 10 000. I have used the equipment for calibrating transformers with ratios from 3 000/5 to 5/5, and did not have the difficulties anticipated by Mr. Hobson. He should note that when the first observation is made R_1 is short-circuited by a plug, so that the standard transformer is on zero burden. The change in the secondary current due to the impedance added by removing the plug is generally too small to affect the result but, if necessary, it can be allowed for.

In reply to Mr. Pocock: It is usual to define "stabilization" as the reduction in the effect of changes in input voltage on the output voltage, and "regulation" as the reduction of the effect of load changes. If the screen of the MS4B is supplied from a battery the stabilization (EdV/VdE) is reduced and the effective internal resistance is increased. Stopper resistances have been used in all the grid circuits from the beginning, and no trouble has been experienced with oscillation.

In reply to Mr. Hawkes: The angle between the vectors of the supply voltage and the current in the "in-phase" slide-wire is less than 15 min. I have measured the errors of voltage transformers: (1) using a vibration galvanometer as detector, and (2) using a cathode-ray tuning indicator with valve amplifier. The results agree to 1 or 2 parts in 10 000. It is not necessary to use stabilized currents when carrying out the tests described in Section 4, because the errors are measured directly and only a moderate accuracy in their measurement is required for the precise determination of the transformer ratio. The modern vibration galvanometer is amply sensitive for all the measurements described in the paper; I have not found it necessary to use an amplifier as suggested by Mr. Freeman.

In reply to Mr. Petch: I have yet to meet an engineer responsible for the periodical checking of standard wattmeters who would not welcome a satisfactory substitute for the H.T. battery. No circuit adjustments are required when a new valve is substituted for one which has failed. The only switch (in practice, a plug) in the secondary circuit of the transformer in Fig. 7 is that which short-circuits R_1. The tertiary winding is not essential to the method (which may be that of Fig. 6c), but is a convenience. The size of the core is given in the text.

FUNDAMENTAL ELECTRICAL CHARACTERISTICS OF SYNCHRONOUS TURBO-GENERATORS

By W. SZWANDER, El. Engr. (Warsaw), Associate Member.

(*The paper was first received* 3rd *June*, 1942, *and in revised form* 11*th October*, 1943.)

SUMMARY

The paper deals mainly with the MVA rating or the power factor rating, and with the synchronous-reactance value of large, non-salient-pole synchronous generators. Essential factors for selecting these values are discussed and a method of making that selection is proposed. An analysis is made of the manner in which the two values affect the operation of the generator. From a power chart based on the classical circle diagram, diagrams of "working area" limitations are derived and represented in co-ordinates of reactive power versus active power, power factor versus active power and excitation current versus active power. These diagrams are suitable both for comparing properties of different generators when ordering new units, and for supervision of operation of generators. Problems of capacitive loads and of synchronous stability of generators are discussed. From a comparison of external characteristics of an isolated generator, with different load characteristics, conceptions of voltage stability and of "absolute power limit" in respect of that voltage stability are derived. The influence is discussed of stator-winding resistance and of saturation on representative diagrams and curves. The paper is illustrated by an example of an actual 50-MW, 58-MVA turbo-generator.

(1) INTRODUCTION

The outstanding importance of a.c. synchronous generators, not only in the electricity supply industry but more generally in the whole technical and economical structure of the modern, highly-industrialized world, cannot be over-emphasized. It is therefore essential that the greatest care and consideration be given to the design and construction of the generators and to conditions of their operation and maintenance. It seems also that the problem of selecting the right type of machine for working in anticipated conditions should receive equal attention; it is not so much the mechanical as the electrical features of the performance of the machine that should be considered. The selection of the best type of generator to be used on a given system requires knowledge both of the theoretical principles of its design and also of different transmission and distribution phenomena in which it plays such an active part. Its design must be such that the best compromise will be obtained between an optimum of its performance on the system and the most economical results of that co-operation. In the present paper a few contributions are made to the solution of the problem of selecting suitable electric characteristics of generators; a complete discussion, however, covering all aspects of the subject is not intended. For example, the economic side of selecting the data of a generator will not be dealt with, though this discussion of the technical aspects of the problem should facilitate an economic analysis at a later date.

A procedure for tackling the problem has not yet been standardized, and accordingly it is difficult to compare the performance and merits of machines offered by different makers in tendering for a contract. Such comparisons must be made. Thus it is useful to lay down fundamental data which an intending purchaser must specify when asking for tenders, and also the particulars which must be supplied by all interested manufacturers. The scope of this paper is limited to high-speed turbo-generators (with solid rotors) having an output measured in thousands of kVA; such machines generate the bulk of electrical energy used at present.

(2) FACTORS AFFECTING THE DESIGN AND PERFORMANCE OF A.C. GENERATORS

(2.1) Factors Beyond the Scope of Present Considerations

The voltage rating of the stator winding, the number of phases and the frequency of the generator must correspond to the system which is to be fed by the machine. The speed of rotation, and hence the number of poles, is determined by technical and economic considerations, mainly in respect of the prime-mover, the steam turbine. Features such as the phase connection in star with an external common point, cooling by means of closed air-circuit with internal or external fans, particulars of excitation, etc., are all more or less determined by the universal trends in construction of generators and usually need not be considered specially by the purchaser.

(2.2) MVA Rating and Rated Power Factor

When selecting a generator, the first and main factor to be decided upon is its output rating, which is usually expressed in terms of the rated MVA, together with the rated power factor. The output rating of a generator must be chosen to suit its anticipated loading when working on the system. The kilowatt rating is generally fixed by considerations of power-plant design and the proposed method of meeting the total load-demand by the available and prospective generating units; it is therefore only the rated power factor which has to be decided in such a way as to safeguard both the best adaptability of the unit to the system requirements and its highest possible utilization factor. The loading of a generator with its maximum active power need not necessarily coincide with the maximum reactive-power load. In the design of a machine, on the other hand, those factors are of importance which result in greatest values of rotor and stator currents as well as of mechanical stresses, therefore the range of conditions under which the generator can be operated cannot be defined simply by a single maximum value of the power rating; it must be described by means of definite limits on a power diagram in kW/kVAr co-ordinates. The adoption of a rated power-factor value (in other words of the rated kVA corresponding to the given kW rating) is, as explained in what follows, affected not only by the expected operational conditions, but also by such factors as the capability of the generator for working with leading power-factor and by its stability in general.

(2.3) Synchronous and Leakage Reactance

Limiting the present considerations to steady-state conditions only, the fundamental electric properties of a generator can be expressed by its magnetization (no-load) and short-circuit characteristics (Fig. 1). From such curves, together with a knowledge of the stator-winding leakage reactance, it is possible to deduce for any working conditions all the values characterizing the operation of the generator: in other words it is possible to construct the basic vector-diagram of the machine for every load. The above method, however, is very laborious, and simplified,

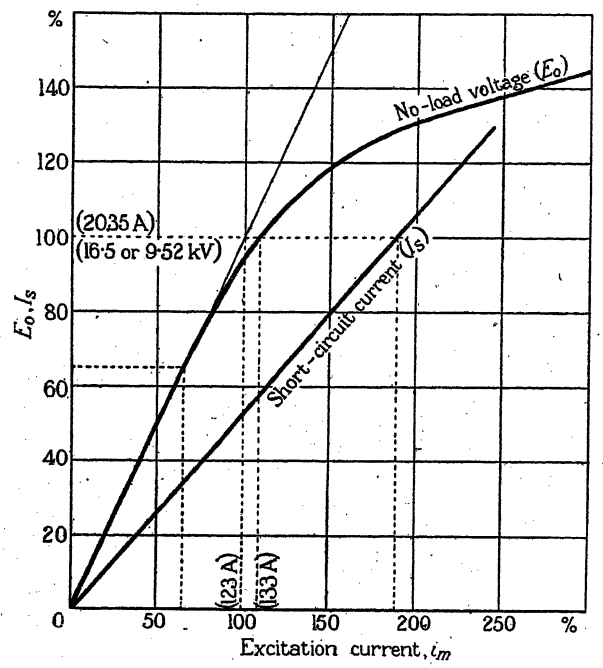


Fig. 1.—No-load and short-circuit characteristics of a 58-MVA, 3-phase, 50-c/s, 3 000-r.p.m., 0·862-p.f. generator.

approximate methods are in use, based on the assumption of non-saturated iron paths in the generator, i.e. a constant value of the synchronous reactance and a straight-line magnetization curve. This simplification permits all the working conditions to be represented by a simple circle diagram; it must, however, not be forgotten that such circle diagrams are approximate, and therefore it is necessary to assess the order of the error due to ignoring magnetic saturation.

The electromagnetic properties of a non-saturated synchronous generator are represented by a single value of synchronous reactance, deduced from the straight-line no-load and short-circuit characteristics. In actual saturated generators the synchronous reactance normally employed to study the performance of the generator when non-saturation is assumed, corresponds to the initial straight part of the magnetization curve. The saturated synchronous reactance decreases with the increase of saturation corresponding to the effective flux at any working point. The constant component of the synchronous reactance, i.e. the stator winding leakage reactance, is of importance when the influence of the iron saturation has to be taken into account in the analysis of the generator's performance.

(2.4) Stator-Winding Resistance

In all considerations concerning large synchronous machines, it is usual to neglect the resistance of the stator windings; the resulting error is negligible. In small synchronous machines the neglect of stator resistance would cause inadmissible quantitative errors in predicting performance. In some cases the results obtained could also be incorrect qualitatively; e.g., in respect of the mechanical power limit of a machine working as a synchronous motor, the very existence of that limit being due only to the presence of the stator resistance.

(2.5) Operation on Infinite Busbars and in Isolation from other Synchronous Machines

In addition to operating correctly under normal loading conditions the behaviour of a generator must also be predetermined and checked in respect of synchronous stability, capacitive loading and voltage stability. It is possible to deduce most of the necessary information if the following two operational conditions are assumed: (*a*) generator connected to a system of infinite capacity, and (*b*) isolated generator supplying a load composed of lighting, heating and induction motors.

Modern systems fed by several generators connected to common busbars, or comparatively solidly interconnected through the elements of the system of sufficiently large capacity, may, as regards each separate generator, be assumed to have a constant voltage which is independent of the load and field excitation of that particular generator; this satisfies the definition of a system of infinite capacity. The above is only an approximate representation, but is sufficiently true since high-speed automatic voltage regulation is commonly used on all systems; moreover, the present considerations are limited to steady-state conditions only. In such conditions synchronous instability can occur only with capacitive loading, and this will be discussed more fully later in the paper. The condition of operation most liable to synchronous instability occurs when a generator supplies power through an inductive impedance (transformers, line, etc.) to a synchronous motor of equal size; this seldom occurs in practice and is therefore unlikely to be a decisive factor in selecting the characteristics of a generator. Such conditions may exist, however, in any system as a transient resulting from an electrical or mechanical fault. When two power systems are connected by a comparatively weak tie-line, operational conditions may also simulate generator-motor transmission, though in each system the generators are supplying power to their local loads. The solution then lies more in so designing the transmission line as to safeguard stability in operation, than in adjusting the characteristics of the generators for the same purpose. Transient instability due to temporary appearance of capacitive load conditions or of generator-motor operation is more likely to occur than steady-state instability. A precise analysis, however, involves great difficulties, and therefore the above cases are usually dealt with by introducing additional safety factors to power limits laid down for steady-state stability; this has proved satisfactory in all but extreme cases.

To sum up, all necessary information concerning the stability of a generator (not of a system) can be deduced by studying its behaviour on a system of infinite capacity.

The regulation of a generator is described by the current/voltage or power/voltage characteristics, the curves referring to a single isolated generator feeding a non-synchronous load. The voltage stability of a system under variable load conditions is a resultant of the voltage stability of all the component generators connected to the system. In other words, if specified conditions of voltage stability are to be satisfied during operation of the system the simplest way to ensure fulfilment is to make each individual generator satisfy the same conditions. For this reason the behaviour of a generator should be analysed also for the condition of working in isolation of any other synchronous machines.

(3) LIMITATIONS IMPOSED BY REQUIREMENTS OF SYNCHRONOUS STABILITY

(3.1) Circle Diagram

The power circle-diagram of a synchronous machine connected to a system of infinite capacity and constant voltage is well known and does not require lengthy explanations. From the vector diagram of the generator (Fig. 2), stator-winding resistance and saturation being ignored (i.e. with constant value of the synchronous reactance X_d), for a constant value of the terminal voltage E_t and with variable load conditions, the following conclusions can be deduced:

(*a*) With a constant excitation current i_m, and therefore also a

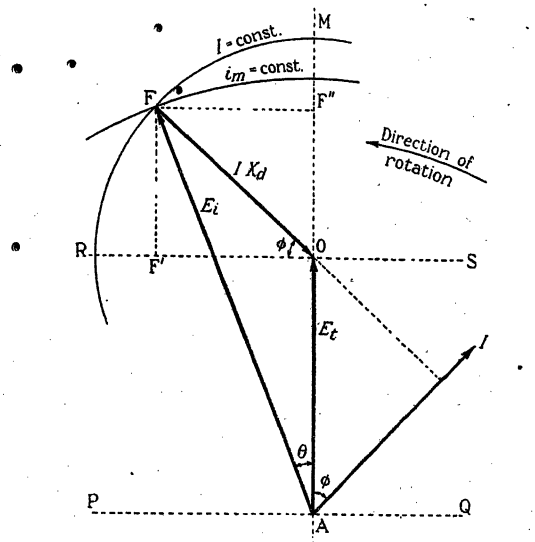


Fig. 2.—Fundamental vector diagram of a synchronous generator.

constant excitation voltage E_i, the "working point" F at all changes of the load must remain on the circumference of a circle drawn from the centre A with a radius $AF = E_i = \text{const.}$

Concentric circles with A as centre will correspond to different values of the excitation current.

(*b*) With a constant stator current *I*, the "working point" F under all changes either of the power-factor angle ϕ or of the excitation current i_m (and the excitation voltage E_i), must stay on the circumference of a circle drawn from the centre O with a radius $OF = I \cdot X_d = \text{const.}$ Concentric circles with O as centre correspond to different values of the current *I*.

(*c*) The projections OF'' and OF' of the vector $OF = I \cdot X_d$ upon the axes of co-ordinates AM and RS represent to a certain scale the values of the reactive and active power at the terminals of the generator, corresponding to the "working point" F. The distance OF represents the apparent power on the same scale.

(*d*) With the adopted anti-clockwise direction of vector rotation, the values of OF' in the direction OR represent the operation of the machine as a generator, and the values of OF' in the direction OS, operation as a motor, the line AM in respect of the situation of the "working point" F dividing the generating and motoring areas.

(*e*) The angle FOR being the power-factor angle ϕ, the values of OF'' in the direction OM correspond to reactive (magnetizing) power flowing out of the machine, whereas the values of OF'' in the direction OA correspond to magnetizing power flowing from the system towards the generator. The line RS thus represents a limit between the area of behaviour of the machine as a "inductive synchronous impedance" (when the points F and A are on the same side of RS) and as a "capacitive synchronous impedance" (when the "working point" F is on the side of RS opposite to point A).

(*f*) The angle FAO is the displacement angle θ between the vectors of the excitation voltage and the terminal voltage; therefore the line PQ represents the synchronous stability limit, and stable operation is possible only when the "working point" F is on the same side of PQ as point O. The distance OA thus represents the largest possible amount of reactive load which the machine can draw from the system without losing stability.

(3.2) Power Chart

A power chart for a synchronous generator, based on the above principles of the circle diagram, is represented in Fig. 3 in a form most suitable for practicable use.* To obtain such a chart, the vector diagram (Fig. 2) has been rotated round the point A by 180°, in order that positive values of active power output of the generator may be represented by positive abscissae in conformity with the common practice. This results in positive ordinates corresponding to the magnetizing power flowing from the system towards the machine, therefore the magnetizing power supplied by the generator to the system must be taken as negative, as opposed to the case of active power directed towards the system, previously defined as positive. The above is in accordance with the rules laid down by

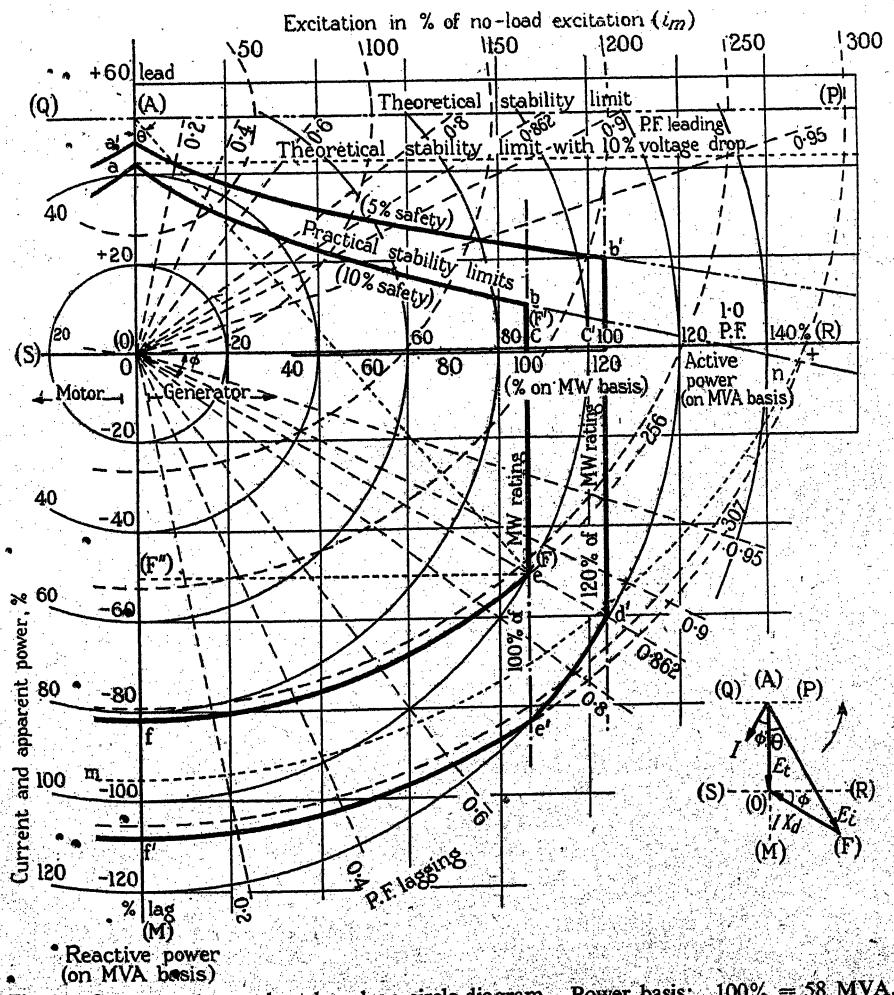


Fig. 3.—Generator power chart based on circle diagram. Power basis: 100% = 58 MVA. Current basis: 100% = 2 035 A. Excitation basis: 100% = 123 A. Terminal voltage: $OA = 16{\cdot}5/\sqrt{3}$ kV = const. Rated power factor: 0·862 lagging. Rated active power output: 86·2% = 50 MW. Saturation and stator winding resistance neglected.

* All the illustrations in the present paper are based on a generator having the following characteristics: 58 MVA, 50 MW, 0·862 (ind.) power factor, 2 035 A, 16·5 kV, 3 000 r.p.m., 3-phase, 50 c/s, synchronous reactance (saturation neglected), 190%, i.e. 8·9 ohms/phase, no-load excitation current at rated voltage (saturation neglected) 123 A. The no-load and the short-circuit curves for this machine are represented in Fig. 1.

the I.E.C., and is a result of retaining the standard anti-clockwise direction of vector rotation, which, in order to preserve uniformity of various diagrammatic representations, is regarded as being most important.

All values on the power chart are represented on a percentage basis. This method is strongly recommended, as it is most helpful when different machines have to be compared. The fundamental scale of the diagram is its power scale with the rated kVA as basis. This "percentage" scale is the same for the apparent, active and reactive power, as well as for the stator current. The distance OA of the stability limit from the abscissae axis, expressed on the general percentage power scale, can be deduced from the vector diagram (Fig. 2) as

$$\frac{Q_s \times 100}{N_n} = \frac{3E_t^2 \times 100}{X_d N_n}\,\% \quad . \quad . \quad . \quad . \quad (1)$$

where $Q_s = 3E_t^2/X_d$ is the reactive power at the stability limit, E_t the terminal phase voltage, X_d the synchronous reactance, in ohms, and N_n the kVA rating of the generator. The distance OA represents also the 100% value of the excitation-circles scale, because the reference value of the excitation current is assumed to be its value at no-load, in which case $IX_d = 0$ and $E_i = E_t$ on the vector diagram. An additional scale for the active power is shown in Fig. 3, having as basis not the kVA rating but the kW rating.

(3.3) Theoretical and Practical Stability Limit

So far as stability requirements are concerned, the "working point" F may be anywhere on the chart surface so long as it is below the stability limit QP. This limit is only of theoretical significance because it represents states of unstable equilibrium, in which even infinitely small increments of load would pull the generator out of synchronism. In practice a proper safety margin must always be observed and the point F should not approach the "theoretical stability limit" QP by more than is defined by a certain "practical stability limit." The most justifiable method of defining the "practical stability limit" seems to be that which depends on having on the "practical stability limit" at every excitation condition the same amount of active power by which the generator load can be increased before reaching the "theoretical stability limit." The graphical construction of such a "practical stability limit" qp is represented in Fig. 4 and is self-explanatory. The assumed constant

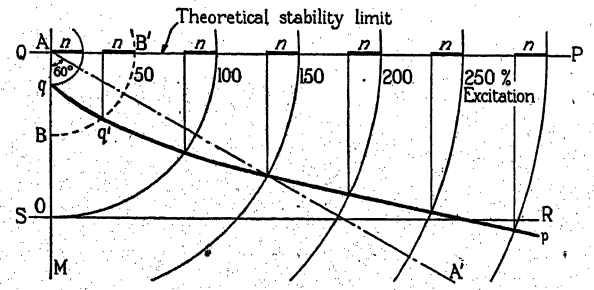


Fig. 4.—Method of determining the "practical stability limit."

active-power increment "n," expressed as a percentage of the machine's kVA rating, represents the "safety factor" of the "practical stability limit." Its value should be so chosen as to suit the possible transient changes of the load, due to faults and any abnormal conditions; usually 10% can be regarded as satisfactory. This method of representing the "practical stability limit" suits the practical requirements better than an assumption that a certain maximum value of the displacement angle θ (e.g. the line AA' in Fig. 4 for $\theta = 60°$) must not be exceeded.

The operation of shunt exciters being unstable at lower voltage, an additional limitation may result in respect of the smallest allowable excitation current (e.g. the circle BB' for 50% minimum excitation in Fig. 4). The two limits BB' and qp combine in such a case to form the resultant "practical stability limit" Bq'p, giving the largest permissible values of capacitive reactive loads. With separately excited exciters, which are used on all large modern generators, the exciter stability is satisfactory down to very low outputs.

(3.4) Effect of Neglecting Saturation

To assess the practical value of the power chart (Fig. 3) the error which results from ignoring saturation must be known. In the case of a saturated machine, the lines of constant excitation current on the power chart will not correspond to constant excitation e.m.f.'s, and therefore will not be represented by circles drawn round the point A; the correct shape and location of those lines on the power chart may be found by constructing exact vector diagrams for several working-points with corresponding values of E_i deduced from the magnetization curve of the machine, for saturation points defined in every case by the actual air-gap voltages. One such "saturated" curve for the constant excitation current of 300% is shown in Fig. 3 (the curve mn), which, when compared with the "non-saturated" circle for the same 300% excitation current, shows clearly that in the region of capacitive loads of a generator the effect of saturation is almost nil. Thus the stability limit of a synchronous machine, based on the simplified, "no-saturation" circle power chart, is practically correct. The error in estimating the excitation currents from the circle diagram (at the highest inductive load with zero power factor) will not exceed 7–8%, and at normal loading conditions about half those figures (readings obtained from the no-saturation chart giving excitation currents which are too small). Thus the simple circle power chart may safely be used for most practical problems.

(4) COMPLETE LOADING LIMITATIONS OF GENERATOR

Besides the "practical stability limit," which gives the maximum permissible capacitive reactive load, corresponding to any value of the active (MW) load of the generator, the power chart can also be completed with other limits, resulting from definite current and power ratings of the machine; such a complete picture of all load limitations of the generator is represented also in Fig. 3. If the generator is so designed that the values of its MW, stator current and excitation-current ratings represent the maximum ratings which cannot be exceeded—then the area a b c e f (in Fig. 3) is the permissible "working area," outside which the working point of the generator should not come. Besides its maximum continuous rating the generator may also possess a certain emergency overload-rating, which may refer as much to the rotor and stator currents as to the MW rating. Under emergency conditions, e.g. when a shortage of plant occurs on a system after some outages, it may sometimes also be necessary to work temporarily with a reduced safety factor of the "practical stability limit." Such an extended emergency "working area" is represented in Fig. 3 by the larger figure a' b' c' d' e' f', for ratings 20% greater than the continuous ratings and with a 5% (instead of 10%) safety factor of the stability limit. The operation of the generator in the "emergency working area" will certainly be allowed only for a definite period, which must be predetermined by the manufacturer.

The limits of the "working area" in Fig. 3 represent the permissible capacitive and inductive reactive loads as functions of the respective active loads of the generator. Making use of the lines of constant power-factor values and of constant excitation currents on the basic circle power chart of the machine, it is

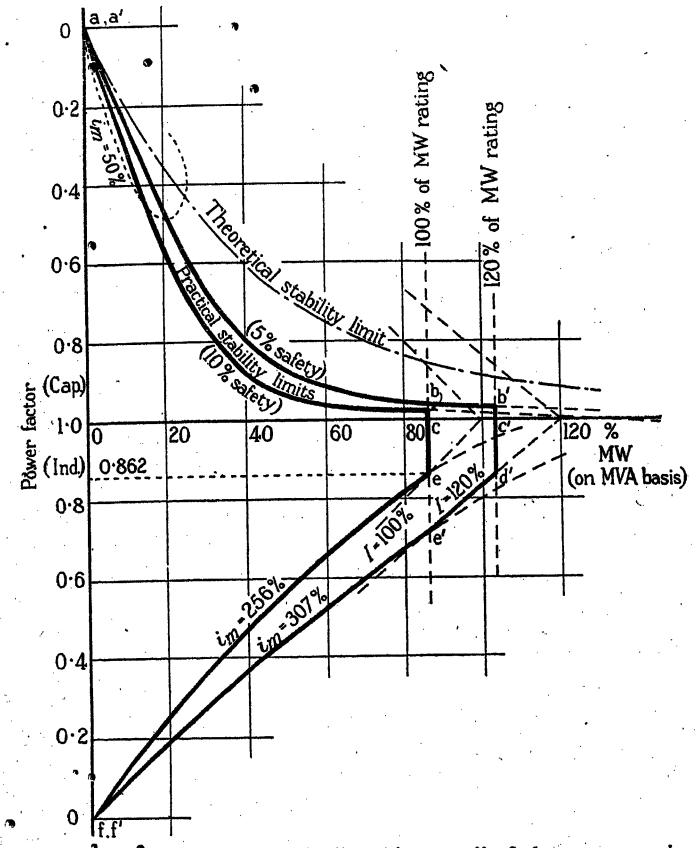


Fig. 5.—Representation of the "working area" of the generator in co-ordinates of power factor and active power. Data as for Fig. 3.

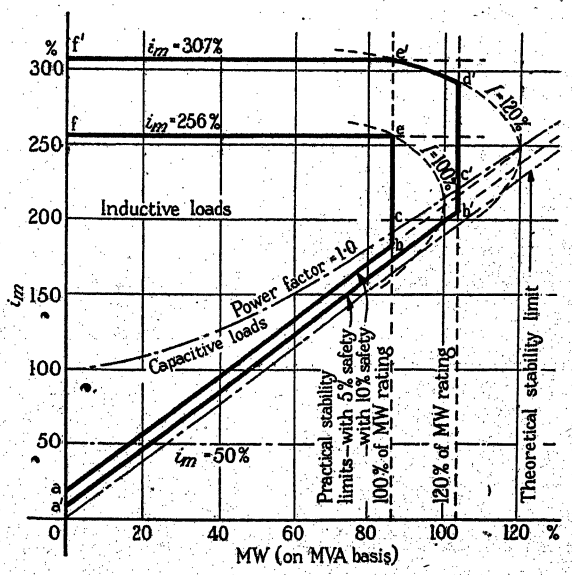


Fig. 6.—Representation of the "working area" of the generator in co-ordinates of magnetizing current and active power. Data as for Fig. 3.

possible to represent the same limits either in co-ordinates of active power and power factor (Fig. 5), or in co-ordinates of active power and excitation current (Fig. 6). The last two methods of representation are in many cases most useful for initial studies of the generators' properties and for supervision of their operation.

(5) CORRELATION BETWEEN THE CHOICE OF SYNCHRONOUS REACTANCE AND MVA RATING OF GENERATOR

(5.1) Influence of MVA Rating on Performance of Generator

When selecting a generator for given conditions of service the machine's loading limitations represented by means of "working area" diagrams must be so chosen as to suit best the anticipated needs of the system. For this purpose it is necessary to know how the limits of the "working area" are likely to be affected by changing the different characteristic values of the generator. In Fig. 7, in addition to the "normal working area"

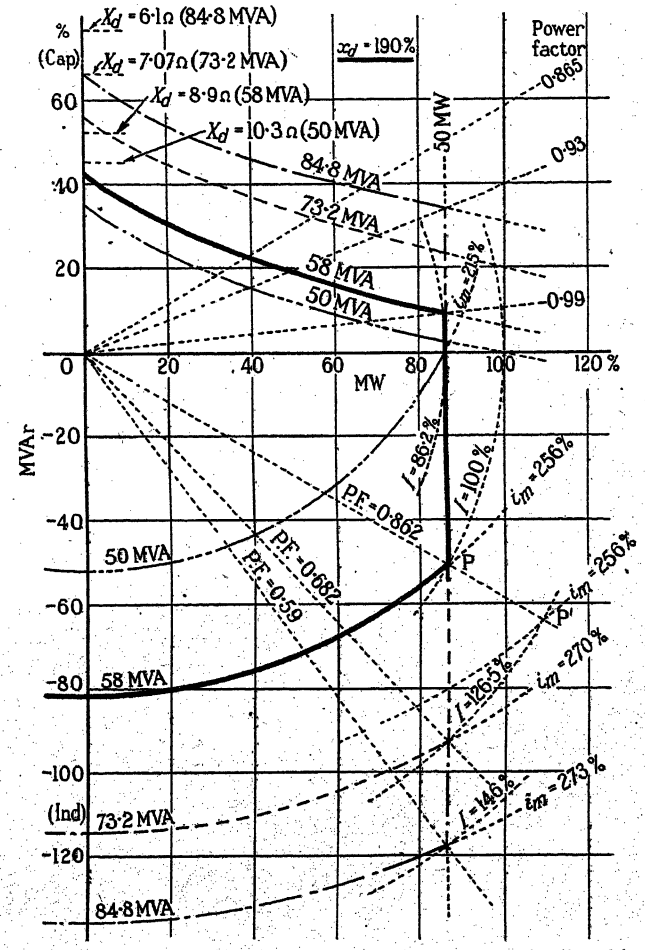


Fig. 7.—Influence of MVA rating of the generator on its "working area" (with constant percentage value of synchronous reactance).

re-drawn from Fig. 3, there are also similar working areas represented for other MVA ratings of the generator. It is assumed that the active-power rating of the machine, and the percentage value of the synchronous reactance (190%) are the same. All the percentage values in Fig. 7 are based on the rated current and power of the initial machine (58 MVA, 0·862 power factor, 2 035 A). The ordinates of the centres of excitation-current circles, obtained from eq. (1) and representing also the distances of the theoretical stability limits from the active-power axis, are for every MVA rating inversely proportional to the ohmic values of synchronous reactance. As a constant percentage value of the synchronous reactance has been assumed, this means that they are directly proportional to the MVA ratings, because

$$X_{d(\text{ohms})} = \frac{3E_i^2}{N_n \cdot 100} (X_d)\% \quad \ldots \quad (2)$$

Thus, as shown in Fig. 7, the increased MVA rating of a generator increases the range of both the capacitive and the inductive reactive load permissible at different values of the active load. The gain obtained, however, is much smaller on the capacitive side than on the inductive side of the loads. It will be noticed from Fig. 7 how difficult it is to increase the capacitive loading range of a generator by increasing its MVA rating: the 50 MW, 58 MVA rating allows an inductive load of 50 MW with 0·862 power factor, but only with 0·99 power factor by capacitive load. An increase of the MVA rating to 84·8 MVA (i.e. by 46%) results in a change of the admissible capacitive power-factor value only to 0·93, at the same time the admissible inductive power-factor decreasing to 0·59.

(5.2) Influence of Synchronous Reactance on Performance of Generator

If a given rating of the generator, e.g. 50 MW, 58 MVA, 0·862 inductive power factor, is satisfactory from the point of view of the range of inductive loads it covers, and the need arises to widen the limits of the "working area" of the generator on the capacitive side only, then an increase in the MVA rating, as represented in Fig. 7, seems to be uneconomical. As the only useful result in this case is the raising of the stability limit, which is due to the decrease of the ohmic value of the synchronous reactance (the last resulting from an increase of the MVA rating with unchanged percentage value of the synchronous reactance), the same result may be obtained if, by keeping the MVA rating of the generator unchanged, a suitably lower percentage synchronous reactance were applied. The same values of the synchronous reactance—10·3, 8·9, 7·07 and 6·1 ohms—which in Fig. 7 correspond to the MVA ratings of 50, 58, 73·2 and 84·8 MVA respectively, at a constant synchronous reactance of 190%, may be obtained from (2) for a constant 58 MVA rating with synchronous reactance figures of 220, 190, 151 and 130%. This is illustrated in Fig. 8 on a "working area" diagram in MVAr/MW co-ordinates referring to a 50-MW, 58-MVA generator, and to the above four percentage values of the synchronous reactance. The resultant changes of the stability limit are accompanied in this case by very small changes of the limit imposed by the maximum excitation current, which in practice may safely be neglected. The maximum-current ratings of both stator and rotor are now being used at the rated-load point (50 MW, 58 MVA), the stator-current rating being the same in all cases, whereas the rotor-current rating increases with the decreasing value of the percentage synchronous reactance. The decrease of the synchronous reactance, at a constant MVA rating of the machine, entails the use of a larger and therefore more expensive generator. The increase in size, however, may in this case be less pronounced than is necessitated by increasing the MVA rating of the unit for the sake of obtaining the same ohmic value of synchronous reactance, because with an unchanged MVA rating the stator-current rating need not be increased and hence the amount of heat to be dissipated remains the same.

(5.3) Method of Selecting the MVA Rating and Synchronous Reactance

It is suggested that the most economic method of deciding upon the MVA rating and the percentage synchronous-reactance value, is to choose the MVA rating according to the requirements of the inductive reactive loads, and then to deduce from the MVA rating and the given capacitive

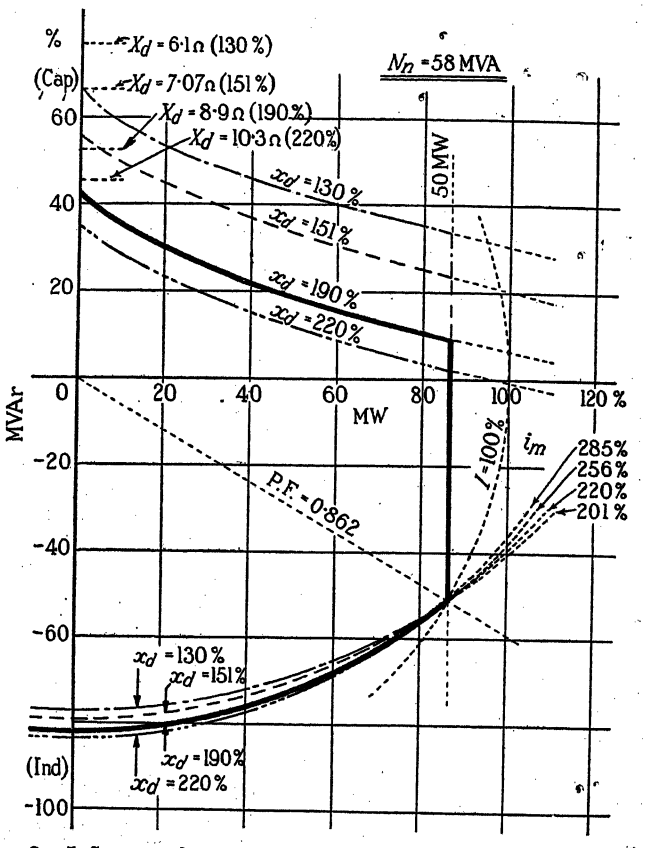


Fig. 8.—Influence of percentage value of synchronous reactance of generator on its "working area" (with constant MVA rating).

load-requirements the necessary percentage value of the synchronous reactance. The first stage of the proposed procedure fixes the stator current: this is the maximum current required by the anticipated loading conditions. It also determines the maximum excitation current, expressed as a multiple of the no-load excitation. The next stage determines the absolute value of the no-load excitation. When choosing the MVA rating and the

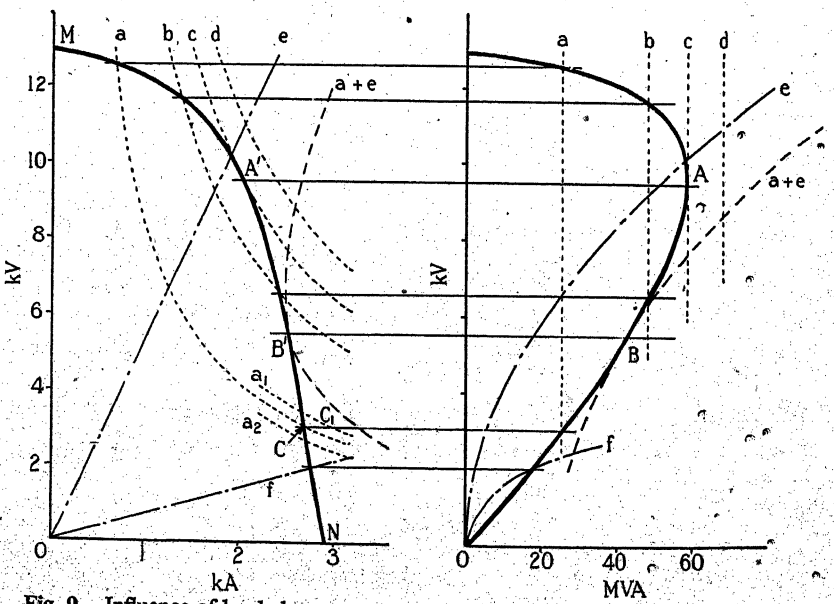


Fig. 9.—Influence of load character on voltage stability of a generator (curves for 0·862 lagging power factor).

percentage synchronous reactance as suggested above, it must be borne in mind that increasing the first and decreasing the second means increasing the size and cost of the machine. The various limits of "working area" of a generator are capable of different interpretations. These limits, which are imposed by limitations of rotor and stator currents, or of the mechanical power, can in some cases safely be exceeded slightly for a short time. This means that the "working point" will enter the "emergency working area," or in exceptional circumstances move even farther, but the safety factors adopted in the design of the machine ensure that this will lead to no serious damage. The situation is obviously different in respect to the stability limit; if this is exceeded the result may be loss of synchronism of the set and subsequent serious disturbance to the system. This will not necessarily happen, as the "practical stability limit" in the diagrams of the generator "working area" embodies a certain safety factor. It becomes more dangerous to exceed the "practical stability limit" the more the safety factor is decreased, and the more frequently transient stability disturbances occur on the system. Though an "emergency stability limit" with a reduced safety factor (as shown in Figs. 3, 5 and 6) may be adopted—the imposed stability limit must be adhered to in order that the system may operate reliably. If the supervisory personnel have at their disposal such diagrams as Figs. 3, 5 or 6 this can be effected more readily.

(6) VOLTAGE STABILITY OF GENERATORS

(6.1) Generator Voltage at Constant Excitation Resulting from Load Characteristics

The considerations of previous paragraphs refer to the working conditions of a generator, characterized by the assumption of constant terminal voltage. In general practice this assumption is justified; the terminal voltage of generators, however, varies to some extent on small systems, and other systems at times of light load when only a few generators are running, also during abnormal transient conditions caused by faults. The behaviour of a generator in such circumstances will depend upon its characteristics when working alone with non-synchronous load connected to its terminals, and those properties are represented by the external characteristics of the generator i.e. the current/voltage and power/voltage curves for a constant excitation current and constant power factor. These curves, deduced from the no-load curve of the machine already used in previous examples, are represented by full lines in Fig. 9. The voltage at the terminals of the generator depends not only on the characteristics of the machine but also on the properties of the connected load, because different kinds of load vary in different ways with changes of applied voltage. In this respect all loads can be represented by the constant-impedance or the constant-power load, or by a combination of the two. If the present considerations are limited to the comparatively narrow margin of voltage-changes which is of practical importance, the lighting and heating loads may be represented with sufficient accuracy by constant-impedance loads, and the induction-motor loads by constant-power loads.

The current/voltage and power/voltage characteristic curves of the constant-impedance loads are represented in Fig. 9 by the lines "e" and "f" for different values of the impedance. For every load (impedance) value, the voltage established at the terminals of the generator corresponds to the point of intersection of the respective load and generator characteristics. In this case no voltage instability whatsoever can occur, as a definite and stable terminal voltage corresponds to any load impedance between infinity (no-load point M) and zero (short-circuit point N). The characteristics of various constant-power loads, represented in Fig. 9 by "a," "b," "c," "d," show clearly that this kind of load cannot be increased beyond a value corresponding to the power limit of the machine (see curve "c"), for beyond it the load and the machine characteristics do not intersect (see curve "d"). For the load-power values below the power limit there are at any load two intersection points with the generator's characteristics, but only at the upper points (between the no-load point and the power-limit point) is the terminal voltage stable.

Usually a generator load is represented by a combination of constant-impedance and constant-power loads, and the characteristic curves for such a combined load may be obtained by adding the curves for the component loads (e.g. curves "a + e" on Fig. 9 drawn for a load resulting from paralleling the loads represented by curves "a" and "e"). The example given shows that for such a combined load there also exists, as in case of the pure constant-power load, a minimum voltage value (the ordinate of the point "B") representing the "voltage stability limit." This limit does not, however, correspond in this case to the maximum load of the machine, but to a point lying on the voltage/power curve beyond the power maximum, nearer to the short-circuit end of the characteristic. Thus in all practical loading conditions the power-limit point of the generator characteristic does not represent the critical point the approach to which means the danger of losing the voltage stability; as every load comprises a certain amount of constant-impedance load also—the critical point of the voltage-stability limit occurs, as a rule, at a voltage which is lower than that of the power-limit point.

(6.2) Power-Limit at Varying Excitation

In the previous Section a constant value of the excitation current has been considered. In practice, however, the automatic voltage regulation tends to counterbalance all changes in the terminal voltage. The behaviour of a machine must therefore be judged by a series of external characteristics for different excitation currents, covering the whole range of their variation. Such a set of external characteristics for the machine to which Fig. 9 refers is given in Fig. 10. The power-limit points on single curves occur with increasing excitations at increasing voltage values—the dotted curve "mn" in Fig. 10 is their locus. A similar curve "m'n'," which passes through the limit points on

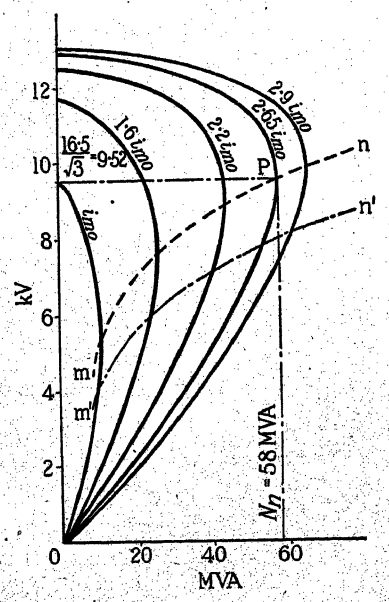


Fig. 10.—Method of determining the "power limits" of a generator in respect of its voltage stability (curves for 0·862 lagging power factor).

individual curves, as defined by the voltage-stability requirements for a given type of load, will characterize the voltage stability of the generator for that type of load. The speed of voltage variations caused by the load-changes is limited by the magnetic inertia of the generator, and with modern design of exciters and automatic voltage-regulators it is possible to keep the terminal voltage constant within comparatively narrow limits. This, however, applies only up to a certain excitation value, corresponding to the point where the curve "mn" (power-limit locus) crosses the working-voltage level (point P in Fig. 10). A further increase of load, and the resultant automatic increase of the excitation current, would bring the working point beyond the power-limit point on the respective external characteristic. In the case of a pure constant-power load this would produce voltage instability, whereas under practical load conditions, though the working point would perhaps remain within the actual voltage stability limit (above point B in Fig. 9), operation beyond the power limit should, nevertheless, be avoided, the margin between the power limit (point A, Fig. 9) and the voltage-stability limit which is difficult to define more exactly (point B, Fig. 9) being regarded as the indispensable safety margin which in practice must be provided for every stability limit.

The point "P" in Fig. 10 thus represents the "absolute practical power limit" in respect to voltage stability, this limit corresponding to a given working voltage (9·52 kV in the example). The term "absolute" is used to distinguish from power limits on individual power/voltage curves for different constant-excitation values. If the power defined by the above "absolute" limit is exceeded it is possible that the zone is entered in which voltage instability may occur under certain circumstances (in respect of load composition). The "power-limit" curve "mn," shown in Fig. 10, refers to the power factor assumed for all the external characteristics in this Figure. As no exact value of the "absolute theoretical power-limit" in respect to voltage stability can be strictly defined (the crossing of some curve "m'n'" in Fig. 10 with the rated voltage level), this value depending both on the character of the load and on its power factor, it is satisfactory in practice to adopt such a "practical" limit as that represented by the point "P" in Fig. 10. (This applies to the rated power factor, and is determined by the curve "mn" passing through the maximum-power points of several power/voltage curves of the generator.) The ratio of the power limit, defined in this way, to the power rating of the generator, represents the permissible overload capacity of the machine in respect of voltage stability. This limitation, resulting from the voltage-stability requirements, is quite as important as the rotor- and stator-current limitations which were represented on the "working area" diagrams (Figs. 3, 5 and 6).

It is not possible to produce without considerable labour a complete set of power/voltage curves at different excitation values, and from this to obtain the power-limit curve "mn" (as in Fig. 10). But at least one power/voltage curve, that for rated power factor and excitation of rated load, should always be investigated. The overload factor of a machine will become the greater, the farther the rated-load point on that curve moves away from maximum-load towards no load. This factor cannot be defined quantitatively, however, without at least two or three points on the curve "mn" in the neighbourhood of the rated voltage level.

(6.3) Importance of Saturation

The external characteristics of the generator, as shown in Figs. 9 and 10, have been deduced from the actual magnetizing curve of the machine, i.e. they take into account the influence of saturation (the stator winding resistance, however, has been neglected). The saturation cannot be neglected in this case, because the errors thus introduced would be so great as completely to change the whole picture. To illustrate this, in Fig. 11 both the unsaturated (full-line) and the saturated (broken) power/voltage curves are represented for the same value of synchronous reactance of 8·9 ohms (i.e. 190% at 58 MVA, 16·5 kV). Up to the rated-voltage level the two curves differ very little and this confirms that saturation can be neglected when dealing with

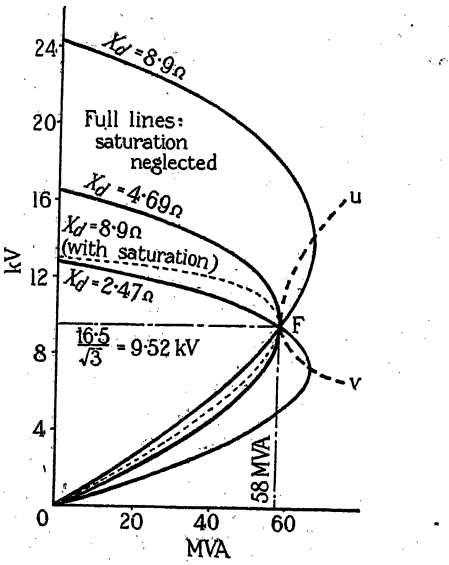


Fig. 11.—Influence of the synchronous reactance of generator on its voltage stability (curves for 0·862 lagging power factor.)

constant-terminal-voltage power charts. Above the rated voltage, however, the discrepancies are very large; the saturated curve has its power maximum at the rated-load point in this particular case, whereas for the non-saturated curve that power limit occurs at a much higher voltage—it is obvious that if based on non-saturated power/voltage curves, any conclusions referring to the position and shape of the curve "mn" in Fig. 10 would be completely false.

(6.4) Influence of Synchronous Reactance

It is important to know how the power limit of a generator, in respect to its voltage stability, can be affected by changes in the design data of the machine. Fig. 11 shows external characteristics of a non-saturated generator for different values of synchronous reactance. The curves are drawn for such excitation values as will cause them all to pass through the same rated working-point (9·52 × $\sqrt{3}$ kV, 2 035 A, 58 MVA, 0·862 power factor, inductive). It will be noticed that when the synchronous reactance is decreased, the working-point F (in Fig. 11) travels along the respective power/voltage curves in the direction of the no-load point. In other words, with a changing synchronous reactance value the maximum-power point of the power/voltage curve moves along a certain curve "uv" representing the locus of those maximum power-points. This curve, as it will be seen from Fig. 11, has a certain minimum-power point; this occurs when the rated working-point of the generator coincides with the maximum-power limit on the corresponding power/voltage curve. This happens (for the non-saturated machine only) at 100% synchronous reactance (on MVA basis of the rated working-point F), the external impedance of the load being equal here to the internal, synchronous reactance, so, as it ought to be, at the maximum possible load of a generator with constant excitation. If it is intended that the rated working-point at the rated excitation shall be above the maximum-power point of the power-voltage curve (and this may be necessary if a greater overload

factor is required), then the maximum-power point of the power/voltage curve must be situated on the lower branch of the "uv" curve (i.e. below the point F) and the synchronous reactance must be less than the "critical" value of 100%.

When taking into account the influence of saturation (which, as already stated, must be done in this case), the computation of external characteristics for different values of synchronous reactances would be very laborious. The presence of saturation will, however, change only the quantitative and not the qualitative aspect of the problem. Although the shape of the maximum-power locus curve "uv" will be different for the saturated machine, yet once again it will have a minimum-power point with which a certain "critical" value of the synchronous reactance will be associated. This value, depending on the degree of saturation (i.e. on the shape of the no-load characteristic), will as a rule be much above the non-saturated value of 100%. In the generator used for all the examples in this paper the critical value is about 190%. The permissible overload factor of the machine will become greater as the synchronous reactance drops below this critical value. Even without determining the limit curves "mn" from Fig. 10 and "uv" from Fig. 11, the position of the rated working point F on the power/voltage curve drawn for the rated excitation, in relation to the maximum power of that curve, will in practice give sufficient information. A decrease in the ohmic synchronous reactance, which affects the shape and the situation of the external characteristics of a generator (as shown in Fig. 11), may be attained either by diminishing the percentage synchronous reactance at the same MVA rating, or by increasing the MVA rating of the machine with unchanged percentage synchronous reactance. As, however, the power limit (determined by the voltage instability) is raised only in order to increase the overload capability of the generator, it will always be accompanied by the necessity to increase the respective rotor- and stator-current ratings also, so that the decrease of the synchronous reactance usually will have to be obtained by increasing the size of the machine. The correct procedure in selecting the electric characteristics of a generator is to select its MVA rating and its synchronous reactance, as outlined in Section 5.3, and then to check these values in respect to the position of the rated working-point on the power/voltage curve for the rated excitation. The result will in most cases prove satisfactory, but, if not, additional corrections to the predetermined MVA rating and synchronous reactance will be necessary.

(6.5) Influence of Direct Connection through Step-up Transformer

Nowadays it is usual to connect generators solidly to their step-up transformers. In such cases it is not the terminal-voltage of generators but the busbar voltage beyond the step-up transformer which is regulated by the automatic voltage regulators, and therefore all the considerations contained in previous paragraphs should refer to current/voltage and power/voltage characteristics based on voltage values beyond the step-up transformer. At the same time the synchronous reactance of the generator will be increased by addition of the leakage reactance of the step-up transformer. The same obviously applies to the power charts and synchronous-stability limits discussed earlier.

(7) ACTUAL OPERATIONAL CONDITIONS OF GENERATOR REPRESENTED BY INTERMEDIATE STATE BETWEEN ISOLATED AND INFINITE-BUSBAR OPERATION

In practice it is exceptional for a generator to supply only its own non-synchronous load, as described in Section 6. The conditions of operation represented by the assumption of infinitely powerful busbars can never be fully obtained in practice. In normal working the conditions of operation correspond to an intermediate state between the above two extremes. The voltage characteristic of a system fed by a number of generators is a resultant of their individual external characteristics. It is possible to represent the voltage characteristic of the whole system at a given point of the system by current/voltage and power/voltage curves of an imaginary equivalent generator, having characteristics made up of the characteristics of individual generators. From the external characteristics of this equivalent generator and from the system-load properties, identical load limitation in respect of voltage stability can be deduced as already described. An exact analysis in detail in most cases being impracticable, it will usually be sufficient to design the individual generators with such properties (overload capacity without reaching the danger zone of voltage instability) in respect to their loads as are required for the whole system, because with identical characteristics of individual generators the properties of the equivalent machine will be equal to those of the components. This, together with the possibility that a generator will be operating alone, explains the importance of taking into consideration the behaviour of isolated generators connected to non-synchronous loads only.

When the terminal voltage of a generator varies, a power chart should be drawn for every different value. In general, however, the voltage of any system is maintained at a constant level by automatic voltage regulation; thus the voltage-changes will be only transient. The limitations of the "working area" as represented in Figs, 3, 5 and 6 will not lose their practical value in such circumstances, because no harm will result from an increase of the maximum rotor and stator currents for a short time, whereas the lowering of the theoretical stability limit caused by a not-excessive transient voltage-drop will not usually bring the theoretical stability limit below the practical stability limit which has been adopted for the above-mentioned diagrams (the theoretical stability limit for an assumed voltage drop of 10% is shown in Fig. 3). If in practice a generator is operated at different levels of terminal voltage (e.g. with different loads on the system) then separate diagrams should be available for these different voltages. Alternatively, the critical (narrowest) limits of the "working area" can be deduced from cases corresponding to extreme values of the voltage, and plotted on one diagram in power co-ordinates. In comparatively few cases, when a proper analysis of the complex problem of system stability, particularly of its transient stability, is indispensable, the information obtained by the methods discussed will represent a valuable stepping-stone to such an analysis. When the electrical data of new generators have to be predetermined, it appears to be neither possible nor necessary to consider the various factors in more detail than has been indicated in the paper.

(8) CONCLUSIONS AND GENERAL REMARKS

The following are the conclusions formulated from the foregoing considerations:—

(*a*) When ordering generators for use on systems in which problems of stability are likely to play an important role, owing to capacitive loads or to large impedances introduced between the individual synchronous generators, their electrical characteristics deserve careful consideration.

(*b*) On important systems supplied by large units, in addition to checking the stability it is essential also to have facilities for proper supervision of loading of generators, in order that inadmissible overloads may be avoided.

(*c*) In order to select the optimum electrical characteristics of a generator and to obtain all the necessary information as to its behaviour in service, it is sufficient to consider the two extreme cases of its operation, viz. in isolation from other synchronous machines and on infinite busbars. Conclusions deduced from the above considerations will in most cases give a sufficient answer to all stability problems; when a more detailed study of transient

stability is necessary, the stability limits deduced from the power charts represent the first approximation to the solution.

(*d*) A decrease in the ohmic value of synchronous reactance of a generator results both in improvement of its voltage stability (increase of permissible overloading factor) and in widening of its "working area" (increase of permissible reactive loads at given active loads). The decrease of synchronous reactance (in ohms) may be obtained either by increasing the MVA rating or by decreasing the percentage synchronous reactance. Both methods entail increase of cost. Decreasing the percentage synchronous reactance for the same MVA results in widening the "working area" only in the direction of capacitive loads, and is more economical than increasing the MVA rating with the same effect.

(*e*) It is suggested that for the given anticipated load characteristics the MVA rating of the generator should be chosen in respect of the inductive loads, and the percentage synchronous reactance should be defined for that MVA rating and for the required capacitive load. The data so chosen should be checked with the permissible overload factor (as defined by voltage stability).

(*f*) Diagrams of "working area" for normal and emergency operation of the generator can be deduced from the power chart and represented in co-ordinates of active and reactive power, active power and power factor or active power and excitation current. Such diagrams are most suitable for supervising generator operation.

(*g*) The resistance of the stator winding need not be taken into account for large synchronous machines.

(*h*) The saturation effect can be neglected when preparing power charts to obtain the "working area" diagrams. This causes practically no errors in the capacitive area, and only moderate errors (below 10%) in the inductive working area. For the more detailed study of system stability (not discussed in this paper) charts based on the magnetization curve of the machine should be used.

(*j*) The external characteristics of a generator isolated from other synchronous machines must take saturation into account. From the no-load and short-circuit characteristics and the leakage reactance it is possible to deduce the external characteristics for any required excitation and power factor. As this entails a laborious procedure, it is suggested that conclusions in respect to the permissible overload factor can be drawn from a single power/voltage curve for the rated power factor and excitation corresponding to the rated working-point.

Some other factors which must be taken into consideration are as follows:—

The leakage reactance, which is a small component of the synchronous reactance (and almost entirely independent of the saturation of the machine), represents a major part of the sub-transient reactance. The sub-transient reactance of a generator determines the initial short-circuit current and thus the mechanical stresses imposed on the elements of the machine during faults, and therefore the general trend toward decreasing the synchronous reactance should not be accompanied by a simultaneous decrease in the sub-transient reactance. If the percentage value of the latter be the same for generators of different sizes, the fault currents will be proportional to the generator ratings. The mechanical strength of generators is also proportional to their ratings.

The satisfactory operation of generators depends largely on the performance of their exciters. It has already been mentioned that, to avoid instability caused by unstable operation of exciters at low output, separately-excited exciters are generally used. Two more points must be noted: the "ceiling" voltage of the exciter and the speed of its voltage-rise in response to field-changes. By keeping these two values sufficiently high the stable operation of generators under transient conditions is assisted. In terms of the methods outlined in this paper—the above tends towards a closer approach to operational conditions of a generator working on infinite busbars, which in turn allows one to set the "practical stability limit," represented on the power charts, nearer to the "theoretical limit," thus widening the "working area" without further decreasing the synchronous reactance.

The following particulars,* when supplied with a generator (or with a tender for the machine), will allow one to analyse the generator's properties in the described way:

(*a*) The MVA rating, the rated voltage and power factor (and hence the rated stator current).

(*b*) The rated no-load and full-load excitation currents.

(*c*) Data of permissible short-time overload of the machine, referring to mechanical and thermal overloads (in terms of active power and stator and rotor currents).

(*d*) The no-load and short-circuit curves on a percentage scale (and hence the non-saturated synchronous reactance).

(*e*) The sub-transient reactance—to be used instead of the stator leakage reactance (this, in conjunction with the no-load and short-circuit curves, allows any other characteristic curves to be deduced).

(*f*) One power/voltage curve (on a percentage scale and taking into account the saturation) corresponding to the rated power factor and excitation current of the rated MVA load [this curve can also be deduced from the previous data, as mentioned in (*e*), but this is a rather laborious procedure].

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* These particulars refer only to considerations covered by this paper, and in every case they will have to be duly supplemented in respect of other factors which at present have not been dealt with.

THE ECONOMIC RATING OF MOTORS AND TRANSFORMERS
AND
THE ECONOMIC FLUX DENSITY IN LARGE SUPPLY TRANSFORMERS

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PAPER No. 1: THE ECONOMIC RATING OF MOTORS AND TRANSFORMERS

SUMMARY

Physical and economic ratings are compared, and the scope and limits of economic choice are discussed and illustrated. A method of economic selection is proposed through the use of larger standard machines, and a technique is developed for investigating the economy of changes in rating. Tables of data and results are given at the end of the paper, and the methods employed in these tables are explained in some detail. The results are expressed in the form of an "economic advantage" obtainable through under- or over-running, and show the former to be highly advantageous in a large number of cases. Methods of implementing the results are discussed.

(1) GENERAL

(1.1) Introduction

The paper was planned as a general inquiry into the economic design and selection of electric motors and transformers. The war has adversely affected its appearance in two ways. Firstly, the various restrictions have made it difficult to publish a paper of length adequate to this study. Secondly, the general tenor of the conclusions is in the direction of under-running—i.e. greater capital expenditure in order to save running costs. But in war-time this is the exact opposite of what is required. At the present time of acute shortage of men and material it is necessary to over-run right up to the danger point. Instead of investing solidly in low-loss plant whose advantage will accrue in years to come, we have to live on our capital, so far as this is physically possible.

But even the war cannot alter the laws of physics or the principles of economics upon which engineering practice jointly depends. An efficiency improvement which pays for itself over 2 or 3 years in plant lasting 20 or 30 is good economics even though we are not able at the moment to follow it out. And soon after the war we may be faced with precisely the opposite situation—an immediate surplus of man-power, and the necessity of planning for high economy in the years ahead.

Moreover, one minor effect of the war has been a general survey of our practice and rules to see whether any of them need tightening up or could be relaxed, and a closer comparison between our figures and those of other countries. If such a comparison reveals a persistent difference in, for example, working flux-densities, such a difference calls for investigation. In particular, the flux density and steel quality in our transformers have been adversely criticized, and after the paper was written this point was specifically investigated by the author and made the subject of a separate paper.†

Under these circumstances the work has been condensed somewhat, and whilst the data and the results for the motors are given in tabular form, some of the reasons for the selection of these data and the methods of certain calculations have been omitted. So far as transformers are concerned the investigation is confined to a single supply price, a single duty and two sizes of large supply transformer.

Since the conclusions depend entirely upon price ratios they will necessarily have to be re-calculated as soon as post-war figures become stabilized. In the meantime these calculations, based on prices ruling some 5 years before the war, will at least serve as a standard of reference. Chiefly, however, the paper should be of value as an illustration of method, and as a permanent contribution to the technique of economic choice.

(1.2) Physical Limits and Economic Rating

Periodically we are promised (or, should one say, threatened with) a revolution in insulation technique. Some new material (probably of synthetic origin), more compact and better heat-conducting and heat-resisting, is going to release us from the bonds which now tie us to the organic world, and we are going to soar to far higher levels of output. Parallel changes are forecast in the other design components, e.g. higher flux or current densities, coupled perhaps with improved ventilation technique, and (in the case of the iron) possibly a change in the material itself or its processing. Some such revolution may become possible at any moment, but before blindly accepting it at its face value as an obvious "improvement" let us examine its implications, and take stock of the economic situation of the user as well as the commercial position of the manufacturer.

If a 10-h.p. frame will provide 12 or 15 h.p. continuously without damage, what is there to prevent us altering the name-plate forthwith? One possible answer is that owing to the cost of the losses it would be cheaper for most users to buy the larger frame for the bigger output: and in fact it might prove to be more economical for the 10-h.p. frame to be de-rated to 8 than to be up-graded to 15. All technical possibilities should therefore be examined from the point of view of running costs before densities are increased or any upward changes are made in our present ratings. The war has taught us the danger of improved technique if it is not wisely directed. In engineering, as in other spheres, there is grave danger of confusing ends and means, and forgetting that a low-priced motor or transformer is only a means to the end of cheap power for the user.

The meaning of economic rating as distinct from physical rating can be explained by a hypothetical example. This is based purely on the assumption of existing manufacturing standards and does not envisage any change in design or any qualitative efficiency improvements. Let it be supposed that 12 h.p. is required for certain hours of utilization, costs of supply, etc. Suppose also that standard machines are listed by the manufacturer, as follows: Machine A rated to give 10 h.p. and Machine B rated to give 12 h.p. at the required speed. Machine

* The Polytechnic, London. (Seconded to Ministry of Fuel and Power.)
† See page 206.

B, although giving 20% more output, costs only 16% more to buy, and has 16% more copper, iron and friction losses.

Now suppose that physical limits can be removed or raised in some way. Owing to technological changes it is possible to run the smaller frame-size* satisfactorily with 10% higher current and flux densities. This machine (under its new label A′) can now give 20% greater output, and will therefore meet the service requirements. Comparing A′ with A, the purchase price is unaltered, and so is the friction loss apart from possible extra fan losses. But both the iron and copper losses will be approximately 20% greater, and therefore some 4% higher than in the case of B. If the machine is an induction motor, the magnetizing current will be very considerably higher.

There are now two alternatives available for the same service,† namely the smaller frame-size over-run machine A′ and the larger-framed normally-rated machine B. A′ will be cheaper to buy but somewhat dearer to run than B. Putting all the factors on some common basis, the overall costs with A′ may be less or more than with B. If less, this indicates that the correct economic rating point is higher than the existing physical rating, so that as soon as it becomes practicable an increase should be made. If, on the other hand, the costs with A′ are more than with B the economic point is evidently lower, and an increase in present ratings would give no advantage to the user even if the whole saving in manufacturing cost were passed on to him.

The opposite process may then be experimented with, using a still larger frame-size. Thus if the next larger standard size listed is rated to give 15 h.p. the economic effect may be tried of running this with 12-h.p. output, suitably proportioned. The object of the present paper is to examine the economy of existing ratings and see whether and where an increase or decrease would be economically desirable. By inference, some idea will be obtained as to how far the change should go—i.e. whereabouts the economic rating point occurs.

The foregoing remarks suggest that in opposing a plan for increased ratings the best strategy is to propose a decrease. Moreover, such a frontal attack, if successful, leads to a more practical line of procedure. For most existing ratings are determined largely by temperature and other limits, and cannot at present be exceeded. Hence, even if economics indicates that a larger output would give cheaper horse-power service, there is nothing to be done about it until technology has advanced. If, however, a smaller output is economically correct, the conclusion is no sterile one but opens up an immense field for immediate action. The plan of "paying for efficiency" is therefore an eminently practical one, wherever it can be proved to be economical, and deserves some further consideration of a general sort.

(1.3) Paying for Efficiency

When Lord Kelvin (then Sir William Thomson) enunciated the law for cables that bears his name he did far more than merely express a rule for choosing conductor sections. He foreshadowed an entirely new principle of design and selection, applicable in some degree to every kind of electrical plant. He and Dr. John Hopkinson were in fact the joint founders of electrical engineering economics.

It cannot be said that the economic principle itself was new. All engineering is necessarily economic, and it is this factor which distinguishes it from applied physics and chemistry. The engineer has not only to get certain physical results but to get them at a price—he has to find not merely *a* solution but the cheapest solution of the problem set him. But design and selection before Kelvin's day (and much of it since) has proceeded on the tacit assumption that the smallest and cheapest machine that will do the job is the right one to install. If the term "the job" really comprises everything that is wanted, this assumption is correct, but usually it does not do so.

The job as usually specified concerns the output performance, coupled with all necessary safeguards in the way of temperature limits and overloads, insulation tests and the like. Lord Kelvin pointed out that the smallest section cable that would "do the job" in this sense was not necessarily the cheapest, because a larger cable might save more in losses than it cost in capital charges.

There are in fact two distinct bases of choice of electrical plant, which may be called output choice and economic choice. The former consists in assembling at the lowest manufacturing cost the lowest quantity and quality of active materials that will give the output required under the conditions specified. (It is assumed that either the specification or the maker's repute will ensure a reasonable life and freedom from breakdown.) The latter consists in a selection such that the capital expenses plus the operating expenses are a minimum.

Both methods of choice are economic in the sense that all engineering is economic, but only the latter is a *specifically* economic choice. The former assumes too easily that the condition of "least total cost" will be satisfied by "least first cost." In the case of cables there are actually two output limitations (heating and regulation), thus making three possible bases of choice. Since all depend on different factors they are quite unrelated, and the correct choice is the largest of the three results. With cables the requirement "least (capital plus running) cost" frequently indicates a larger size than either of the other bases, and economic choice is then relevant to the engineer and should dominate his actions.

The feasibility of extending this method of choice to other electrical plant follows from two simple statements which can be categorically made: (*a*) The cost of the losses in electric power plant is usually as much as the cost of the plant itself (both reckoned on the same basis), frequently 2 or 3 times as much, and sometimes 5 or more times as much. (*b*) The losses can almost always be reduced by a greater capital expenditure.

These facts are rarely appreciated by either designer or purchaser, and their full implication is almost completely disregarded.

One reason for this disregard is the uncertainty as to whose business it is—whether it is a problem for the manufacturer or for the user and his consultant. If greater capital expenditure is to be employed (beyond the minimum necessary to comply with existing specifications) in order to obtain smaller losses and lower total costs there is no doubt that the designer is in a position to give the best value for this money. The user arrives late on the field and can only select from existing patterns, none of which is probably ideal for his purpose. But in a fiercely competitive world it is difficult to sell a high-efficiency, higher-priced article unless large-scale publicity or corporate action is undertaken in order to create a demand.

(1.4) Should Efficiency be Specified?

The manufacturer has no direct responsibility for, and may even disclaim any interest in, how his machine is used or what its performance is apart from output and reliability. He may reasonably say "I have a specification to which I am asked to work, and my task is to turn out the cheapest machine complying with these requirements. If a client values other items such as efficiency so highly as to be prepared to pay more on this account he should embody an efficiency requirement in his specification."

It would certainly seem that the logical solution is to widen the basis of "the job" so as to include a certain minimum efficiency. Attractive though this plan is, there are several pitfalls.

* The term "frame size" refers to the spatial dimensions, weight, etc., of the plant as distinct from the rating or name-plate data and the way it is used. A machine (A′) of the same frame-size as A means an identical machine materially with the same dimensions, price and weight of materials, but with a different label and usage.

† They can hardly be identical in performance, e.g. overload capacity, but it is assumed that any such differences are immaterial for the purpose concerned.

There are situations in which, owing to a combination of low energy price and short hours of use, efficiency is comparatively unimportant. If the minimum efficiency is specified so low as to meet the least-cost requirements of these marginal situations, it will probably be no better than is already obtained through the operation of temperature limits and heat-dissipation considerations. If considerably higher efficiencies are called for, this will ensure a better machine for the great majority of situations but there will always be circumstances which will make such a machine extravagant. Variations in duties and tariffs are so considerable that the value of efficiency varies enormously with the situation; and any figure high enough to be worth demanding would be too high for some places, and might seriously embarrass the manufacturer when competing in markets where the writ of the B.S.I. does not run.

There are other difficulties involved in an efficiency specification. A glance at the Tables in the present paper serves to show not only what a large number of variables are involved but also how many of these have qualitative as well as quantitative differences. The supply tariffs may be of any magnitude and of several different types. The use periods vary not only in length but in character, and have a varying probability of overlapping the demand peak period. The loading within the period also varies, and the shape (as distinct from the height) of this loading curve affects the costs of certain of the losses.

Finally, efficiency is too loose a term. If with efficiency we couple power factor, there are at least four different kinds of waste consumption which may be comprised within it, namely series copper loss, iron and shunt winding losses, friction loss and magnetizing consumption. Each depends on a different variable and may have a different cash value. It would be quite possible to vary the proportions of these losses so as to get the same efficiency with entirely different economic results.

(1.5) Method and Cost of Efficiency Improvement

A difficult question to decide is what figure to estimate for the cost of building to a higher efficiency. The cost of making an article depends largely on the number required, and the cost of a single special machine would usually be fatal to any economic endeavour. Moreover, even the manufacturer with a perfectly free hand and a large potential market for the higher-grade product might find it difficult to estimate beforehand what the cost would be. The upshot is that far the simplest way of investigating the economy of high efficiency is to postulate the under-running* of standard machines, based on existing ratings and manufacturing costs. Not only is it the simplest way of obtaining data on which to work, but it is in many cases the only possible method of implementing the results of the investigation.

The point can be seen most clearly in the case of a machine without friction loss, i.e. a transformer. Thus a purchaser requiring a 750-kVA transformer which is listed to have a full-load efficiency of 98·3% may have reason to think that his situation would justify paying extra to get an efficiency of 98·5%. Finding that the next larger size, namely 1 000 kVA, is listed to have this efficiency, he can safely assume that the simplest and probably the cheapest way of securing such an efficiency is by buying the larger transformer and under-running it. If the under-running is the same in the two directions the full-load efficiency will be maintained intact on the lower output. Thus if he requires a l.v. output of 750 kVA at 400 volts he will order a transformer to give 1 000 kVA at 460 volts, so that in operation he will be under-running both iron and copper by 13%. (He could, of course, obtain a still higher efficiency by proportioning the under-running according to the initial values of the losses, but it does not follow that he would obtain a higher degree of economy.)

Summing up, it may be said that there are, broadly, two methods of efficiency improvement, the qualitative and the quantitative. The former is likely to be more effective, since a design which is deliberately aimed at high efficiency from the outset may, by the use of higher-grade materials and more expensive assembly, avoid the necessity for bigger frame sizes. The latter method, consisting merely of the employment of larger amounts of the same active materials, involves larger structures whose additional friction may nullify some of the gain. This method, which is the only one envisaged in the present paper, therefore represents the irreducible minimum; and one may assume that, if a case for improvement can be made out on this basis, a much better one will lie by the other method when available.

(1.6) Single Example

A situation in which efficiency improvement is almost always worth paying for occurs with induction motors operating long hours on a medium or high tariff, particularly if there are power-factor penalties. An example of this is given below, and it also serves to illustrate the procedure of under-running for efficiency improvement.

Let it be supposed that the service required is 8 h.p., 970 r.p.m., on a 400-volt 50-c/s circuit, and that a protected-type squirrel-cage motor is called for. It will further be assumed that the motor is connected for 46 hours a week with a mean load during this period of only 70% of the rated output (i.e. 5½ h.p.), but with a full 8-h.p. load at the time of the consumer's peak. The following calculation is based on prices ruling some years before the war, and the tariff is taken at a normal figure for l.v. industrial supplies, namely £6 per annum per kW or per kVA plus 0·5d. per kWh.

A motor to the above specification was tendered at £11 10s. with full-load efficiency and power factor of 85% and 0·90 respectively. The electrical losses were made up of 300 watts iron loss, 560 watts full-load copper loss, and 3 360 VAr magnetizing consumption. Although these losses are, if anything, below the average for this size of machine, their cost on the above duty is £7 11s. per annum on the kW tariff and £12 5s. p.a. on the kVA tariff. Thus even without power-factor penalties the iron and copper losses cost each year two-thirds of the motor purchase price.

The ideal way of applying economic choice to the above situation would be to re-design the machine, using more or better active materials, higher-grade insulation and a more compact assembly, so that the losses were smaller and the magnetizing current less. If there were any increase in friction due to larger size of frame this could be more than balanced by decreased fan losses (less internal heating having to be dissipated). But a special machine is expensive to manufacture, however cheap it may be to run, and such a plan would be justified only if a large order were concerned. For a single motor the simplest procedure is merely to use the next largest (standard) machine and under-run it.

In the present case the 10-h.p. motor of the same manufacture is priced at £13 10s., with full-load efficiency and power factor of 86% and 0·91. If this machine is ordered for 440 volts and is then run at 8 h.p. on 400-volt mains (so that both copper and iron will be working at about 10% below rating), its losses and magnetizing consumption will be materially less than those of the standard 8-h.p. size. The annual cost of the electrical losses on the kW tariff will be £7 3s., which represents a saving of 8s. per annum over the smaller machine. This saving can be capitalized over a 20-year life at a present worth of about £5, so that the saving is 2½ times the cost of obtaining it. Another

* Under-running, on economic grounds, must be clearly distinguished from under-loading, as usually practised. The former means reducing both the iron and the copper densities in suitable proportions, whereas the latter is a reduction of the current loading only.

way of putting it would be to say that the extra cost of the larger machine would be recovered in the first 5 years of operation. On the kVA tariff the extra cost would be saved in a single year's electricity account.

(1.7) General Case

The above type of economic choice between specific alternatives is a fairly obvious one. It has been treated elsewhere by the present author and others,* and no further examples need be given here. When two (or more) alternative quotations are tendered for the same service, one at a higher price and efficiency than the other, it is a comparatively easy matter to select the most economical machine for any given set of conditions. The objections to these *ad hoc* calculations are as follows:

(*a*) Working conditions vary so enormously and machine sizes and types are of so wide a range that one might work out many hundreds of such cases and still establish no general principle. (*b*) Owing to the exigencies of standardized manufacture it is not very often that a clear-cut alternative of price to efficiency is available. (*c*) Such a choice can only be made between two or three distinct alternatives, whereas to find the true point of economic rating one must be able to envisage the choice in terms of small gradations over a complete range of alternatives. (*d*) As already explained, efficiency is too broad a factor and must be analysed into its component parts. Choice based merely on this overall efficiency value, and proposals for under-running in the rough undiscriminating manner illustrated in the above example, will never yield the optimum economic results. Thus in the above case it will be found from later results that the correct procedure would be to under-run the copper alone on the kW tariff and the iron alone on the kVA tariff.

What the present paper attempts is not so much a set of particular cases as something in the nature of a general solution. It endeavours to survey, though only in outline, the whole situation as regards the economic choice of constant-speed motors† and large transformers. It describes a method (and tentatively some values) for establishing the point of economic rating, with particular reference to the economics of higher efficiencies obtained through lowered outputs from existing frame-sizes. It endeavours to discover for what sort of situation the existing designs are economic, and how far such designs are wrong for the average case. The results of such an inquiry should indicate the kind of situation where economic choice is feasible, i.e. where it is likely to indicate a bigger capital outlay than the minimum necessitated by existing output requirements.

For this purpose a special technique of economic choice has been developed, as described below. In the foregoing case a larger machine than necessary was installed in order to save losses: in effect, more iron and copper was purchased so as to reduce the flux and current densities. When carried out by the purchaser, such a procedure can only take place in jerks (a 10-h.p. size instead of an 8-h.p., and so on)—it is in no sense a continuous function. But it can, in theory, be regarded as one step in a continuous process, and if carried out by the designer it might be so in practice. Something like a general mathematical solution then becomes possible.

(1.8) Technique Employed

Data are first obtained for a complete range of standard machines of the required type and speed. The prices and the chief losses are expressed as functions of the normal horse-power or kilowatt output. It is found that in every case these can be very closely represented by a simple power less than unity—i.e. $P = kH^n$, where P is the price, the power lost or the magnetizing consumption, H is the normal horse-power or kilowatt output, and k and n are constants, n being less than unity.

The method followed is roughly that indicated in the hypothetical example on page 195 except that each group of losses is taken in turn, and only a very small change is considered. This has the advantage that it is then quite immaterial whether an increase or a decrease in rating is postulated. For if, say, a 1% increase in current density produces a certain overall economic result, a 1% decrease will produce an exactly equal and opposite result.

Let it be supposed that the required output is in the neighbourhood of 100 h.p., and that a standard machine A is listed to give exactly this output (at the required speed) at a certain price and with stated losses. Consider now the extra cost of obtaining a 1% larger output at the same speed, by various alternative means. If a standard machine B were listed to give this output, its price and losses would be indicated by the formula $P = kH^n$, where H has the value 101 instead of 100. This does not mean that a 101-h.p. motor could actually be purchased for this (since such a size is unlikely to be listed) but merely that, if it were, its cost based on existing mean prices over the range would be this much. The losses are connected with horse-power in a similar manner.

Now if $P = kH^n$ the effect of small changes δP and δH is given by $\delta P/P = n\delta H/H$, i.e. the proportional change in P is n times the proportional change in H. Thus if n were 0·8, a 1% change in H would produce a 0·8% change in P. The extra cost of, and the extra losses* due to, 1 additional horse-power at this point of the range can thus be calculated for the normally rated plant.

In the second place, suppose that physical limits allow the initial size of motor to be run with 1% greater current density. The output will increase by 1% and the copper loss by approximately 2%. (The precise value for this and other indices is discussed in Section 2.) The price and other losses will be unaltered. Thus the cost of obtaining 1 extra horse-power by this means, which may be called A′, will be merely the cost of this extra copper loss.

Provided each of the losses can be given a capitalized value it is then possible to compare the overall cost of 1 additional horse-power by two different means, a larger machine B and an over-run machine (in the current direction) A′. If A′ is materially cheaper then it is evident that the normal current density is below its economic value; and if physical limits permitted there would be an economic advantage in pushing current densities up, not merely by 1% but probably by an appreciable amount. If, on the other hand, B is materially cheaper, then the present current densities are too high economically for the situation considered, and a reduction would save money for the user. Such a reduction might prove advantageous over a considerable distance, i.e. there might be a case for paying for a material increase in the efficiency (in respect of copper loss).

As a third possibility (starting again from the initial machine A), suppose instead that the flux density can be increased by 1%. This also will give a 1% higher output machine A″ at the initial purchase price but with larger iron losses and magnetizing consumption. The overall costs of the extra horse-power gained in this way can be compared with that of the standard-rating larger frame-size B. As in the other case, the overall costs may show either an advantage or a disadvantage in the over-run machine. If the latter, an equal advantage would lie in under-running.

It will be seen that the technique employed is to take each group of active materials in turn and to explore the economic

* See "Electrical Engineering Economics" (Chapman and Hall) and a recent paper by Sir Frank Gill on "Engineering Economics" (*Journal I.E.E.*, 1943, **90**, Part I, p. 373).

† Variable-speed motors have been omitted from the numerical work because of the greater difficulties attending the loss calculation, but there is no reason to believe that the economic point is materially different from that of shunt and induction motors.

* Throughout this paper the extra friction loss of the larger frame-size machine has been neglected and only the electrical losses have been considered. This is because, although a 1% larger frame-size machine must be expected to have slightly larger bearing friction and core windage, the smaller machine when over-run will almost certainly necessitate increased fan losses. These have also been neglected (there being no data on which to estimate them), and it is believed that the two omissions in the compared machines will approximately cancel out.

effects of small changes in the quantities of these materials. The economic rating point (or point of cost equilibrium) in respect of any such material may be said to be reached when a small change in its quantity or quality produces equal and opposite effects on the cost components and therefore zero effect on the overall cost. At this point an additional £1 of capital expenditure just saves losses valued at £1. If physical limits did not exist, the correct design would be to expand or contract every element capable of independent variation until each in turn reached this economic rating point. In economic parlance, if the copper, iron, etc., be regarded as being added to the structure in a series of small increments or doses, there comes a point when a condition of economic saturation is reached for that particular variable. The increment at this point is described as the "marginal dose" or as having marginal utility, since the gain thus obtained only just pays for its cost.

It will be obvious that the above process only gives the correct economic choice, not the correct engineering choice. Since temperature rise, regulation and all other physical limits have been neglected, the correct size economically may well prove to be unacceptable on one of these other grounds. As already explained, each of the several bases of size determination must be worked out in turn, and the largest of the sizes indicated should then be specified.

(1.9) Worked Example

Consider a 1 000-r.p.m. cage-type machine for which H = 10 h.p. (values correct to two significant figures only). The various constants employed are explained in Section 2, but references to the actual Tables are given below.

Normally Rated Machine (A).

Line.			
1.	Price = $2{\cdot}4H^{0{\cdot}75}$ (Table 6)	= (£)	13·5
2.	Copper loss = $0{\cdot}106H^{0{\cdot}79}$ (Table 6)	= (kW)	0·66
3.	Iron loss = $0{\cdot}055H^{0{\cdot}80}$ (Table 6)	= (kW)	0·35
4.	Magnetizing consumption = $0{\cdot}66H^{0{\cdot}78}$ (Table 6)	= (kVAr)	4·0

The following are the extra costs (by three methods) necessary to get 1% more horse-power, under conditions of "cheap" capital, "medium" energy price, Duty 4; first without, and secondly with power-factor penalties.

Method 1: *Using* 1% *Larger Machine* (B).

Line.		
5.	Extra plant cost = 0·75% of 13·5	= (£) 0·10
6.	Extra copper-loss cost = 0·79% of 0·66 × 54 (Table 5)	= 0·28
7.	Extra iron-loss cost = 0·80% of 0·35 × 83 (Table 5)	= 0·23
8.	Total, excluding p.f. penalty	= 0·61
9.	Extra magnetizing cost = 0·78% of 4·0 × 26·8 (Table 5)	= 0·83
10.	Total, with p.f. penalty	= 1·44

Method 2: *Using Over-run* (*Copper*) *Machine* (A').

Line.		
11.	Extra copper-loss cost = 2·1% of 0·66 × 54	= 0·75
12.	Balance against over-running if no p.f.p. (Line 11—Line 8) [Ratio 2·3]	= 0·14
13.	Balance for over-running if p.f.p. (Line 10—Line 11) [Ratio would be negative]	= 0·69

Method 3: *Using Over-run* (*Iron*) *Machine* (A'').

Line.		
14.	Extra iron-loss cost = 1·9% of 0·35 × 83	= 0·55
15.	Extra magnetizing cost = 4% of 4·0 × 26·8	= 4·27
16.	Total, with p.f. penalty	= 4·82
17.	Balance for over-running if no p.f.p. (Line 8—Line 14) [Ratio 0·4]	= 0·06
18.	Balance against over-running if p.f.p. (Line 16—Line 10) [Ratio 35]	= 3·38

(1.10) "Economic Advantage" Ratio

When the figures show a considerable disproportion between the alternatives it is convenient to express the extent of this in the form of a ratio. Thus, suppose that the larger frame-size machine (B) costs £5 more in purchase price, but that the smaller machine when over-run (in a specified direction) so as to give the same output has extra losses (in excess of B*) costing £15. The contrary action is therefore indicated, and, by the same figures, under-running to the extent of £5 extra expenditure on plant would save £15 in losses cost. There is then an economic advantage for under-running represented by a ratio of 3 to 1.

In mechanics one speaks of the "mechanical advantage" of a lever or machine in the form of the ratio between the forces (effort and load) on the two sides. The term "economic advantage" is here used to indicate the corresponding ratio resulting from any given change (= financial return divided by expenditure required to obtain it). The return and the expenditure must of course be evaluated on a common basis, e.g. annual costs or capitalized costs. Another point is that the "financial returns" are the gross returns after subtracting any advantages accruing to the other machine but exclusive of the capital expenditure.

The example worked above shows the results in the form of differences, but it can easily be extended to show ratios. Thus for machine A' the figures show that without power-factor penalties there is an excess loss due to over-running the copper by 1%, the cost of which is 0·75 (Line 11) minus 0·51 (Lines 6 and 7) = 0·24. Conversely, there would be a gain of this sum due to under-running by that amount. Now the cost of under-running by 1% is the extra plant cost of purchasing a 1% larger-output machine, namely 0·1 (Line 5). The quotient 0·24/0·1 = 2·4 (more exactly, 2·33) is then the "economic advantage" ratio. (Figures given in square brackets.)

The result given in Line 12 could therefore be expressed by saying that extra expenditure on copper would save losses worth $2\frac{1}{3}$ times this expenditure, when evaluated on a common basis. Comparing annual with capital costs, the extra capital expenditure would be recovered in $11{\cdot}8 \div 2\frac{1}{3} = 5$ years of operation.

It will be noted that the "economic advantage" ratio may be less than 1 or even negative. A ratio of less than 1 means that the gain from under-running is less than the plant cost of obtaining it and that under-running is disadvantageous. A fractional value therefore shows that under-running is contra-indicated. When the calculated ratio comes negative (showing that the larger machine actually costs more in losses than the smaller machine) this is represented in the Tables merely by a minus sign, since the numerical value has no practical significance. A negative sign therefore indicates that under-running results in a loss even apart from the extra plant cost.

The results of the present paper are all expressed in the form of this "economic advantage" ratio. Thus a figure of 3 in Tables 7 and 8 shows that under-running is advantageous, and that for small changes in that direction the return will be 3 times the expenditure, i.e. the extra values or reduced costs are worth 3 times the extra capital incurred. A figure of 0·5 shows that over-running is advantageous, and that a small increase in rating will be worth twice the cost of making it.

(2) NOTES ON TABLES. RESULTS AND CONCLUSIONS

(2.1) Bases of Comparison

It is axiomatic that one cannot compare different kinds of things, and when a capital expenditure has to be weighed against an annual saving they must both be put on the same basis for any exact comparison. The two commonest bases of economic appraisal are total capitalized costs (over the lifetime of the plant)

* Note that the comparison must be made on the basis of identical outputs. Hence the losses of A' must be compared not with those of the original machine A but with those of the large frame-size normally-rated machine B.

and total annual costs. The two give identical results, and both equally require estimates of useful life and rates of interest. In fact, no decision involving a comparison between present and future occurrences can be made without an implicit judgment on these two points. In the present paper the capitalized-costs basis has been employed throughout, quarterly payments being assumed for all items.

An alternative, less precise, method of comparison is preferred by some industrialists who dislike the hire and life assumptions (interest and depreciation) necessary for the above methods. Particularly when an extra capital expenditure is mooted in order to effect an annual saving, the commercial manager may require a more forceful mode of expression before he will sanction any avoidable outlay. He may then wish to know what is the period of years within which he can expect to see his money back.

An effective plan then is to express the simple ratio of the capital expenditure to the annual saving. Since the annual costs in this paper have been capitalized by multiplying these by 11·8 it is only necessary to divide 11·8 by any one of the ratio numbers given in Tables 7 and 8 in order to get the time, in years, of this capital "return period." (See example in Section 1.10 regarding machine A′.)

(2.2) Life and Salvage Value

The economic life of a machine is the length of time for which it is useful in its original capacity and situation. At the end of this time it may still be in working order, or even "as good as new," but owing to some change or other, economy requires its replacement by something different. Its salvage value then will be only a small proportion of its initial cost. If an induction motor or transformer is used right up to the point of being completely worn out or obsolete its life may well be 30 or more years, but its value then will be merely a scrap or break-up figure and barely sufficient to pay for removal. A more likely figure for the economic life will be from 15 to 25 years, with a 10% salvage value at the end of the time.

In the present paper a uniform life of 20 years has been assumed, with zero salvage value at the end. This represents only about 18½ years with a 10% salvage value, and so it may be regarded as a conservative estimate. In order to cover all other likely cases Table 1 has been prepared, showing how the results of the paper can be modified to suit other life assumptions.

(2.3) Capital Charges

The capital charges have been calculated for two different situations, described as "cheap capital" and "dear capital." The former, representing public corporations, large utility undertakings, etc., assumes an interest rate of 5% on the loan and 3½% on the depreciation reserve (or 5⅜% when the rate is the same on both). The latter, representing those bodies less favourably placed in the matter of credit facilities, assumes 7% on the loan and 5% on the reserve fund (or nearly 8% as an overall figure).

Table 2 gives the total percentage allowance (to cover interest and depreciation) which has to be made when using the annual costs basis. It also gives the corresponding figure required for the capitalized costs basis, namely that which has to multiply all annual sums in order to express their present capitalized value. (It will be realized that the figure of 11·8 is the present worth of 20 end-of-year payments of £1 at the appropriate rates of interest, and is the reciprocal of $\frac{8{\cdot}47}{100}$.)

(2.4) Supply Price

Referring to Table 3, the price paid for the supply at any point is taken as being comprised in one or other of the three sets of figures given, under the headings "cheap," "medium" and "dear." The figures under cheap energy are intended to represent a bulk-supply price, or the costs of an efficient private station situated near or at the point of utilization. They are, in round figures, the pre-war Grid tariff. Medium energy is intended to cover a.c. supplies at either high or low voltage in situations which are normally placed as regards supply costs. Dear energy is for l.v. supplies at points where the distribution costs are high or where consumption is on a small scale.

These figures are in a fairly uniform sequence of 2·: 1 in magnitude, but they are cast into a two-part form with different ratios between the two parts. Hence, by using suitable multiplying factors, one or other will serve for any two-part tariff likely to be met with.

(2.5) Power-Factor Costs

In Table 3 it is assumed that variations of power factor affect the fixed charge only and not the running charge. It is further assumed that the form which the charge takes is that of a flat rate per annum per reactive kVA. Over the working range of

Table 1

USEFUL LIFE OF PLANT

Assumption	Multiplying factor for Tables 5, 7 and 8	
	Cheap capital	Dear capital
25 yr, zero salvage value	1·12	0·94
20 yr, zero salvage value; or 18½ yr with s.v. 10% of first cost	1·00	0·85
15 yr, zero salvage value; or 13¼ yr with s.v. 15%* of first cost	0·84	0·73
10 yr, zero salvage value; or 8½ yr with s.v. 20%* of first cost	0·63	0·57

* These figures have been taken because if removed after 8 to 13 years the plant should still be worth 15% to 20% of its first cost.

Table 2

CAPITAL CHARGES (20-YEAR LIFE)

	Rate of interest—			Combined charge for interest and depreciation	Capitalizing coefficient
	On loan	On sinking fund	Equivalent rate if same on both		
Cheap capital	5%	3½%	5⅜%	5 + 3·47 = 8·47%	11·8
Dear capital	7%	5%	7⅞%	7 + 2·94 = 9·94%	10·06

Table 3

SUPPLY PRICE

Energy referred to as	"Cheap"	"Medium"	"Dear"
Running charge (per kWh)	0·2d.	0·5d.	1d.
Standing charge (p.a. per kW)	£3	£6	£10
Numerical ratio between parts	15	12	10
Power-factor charge (p.a. per kVAr)	15s.	£3	£6
Corresponding annual p.f. penalty (at about 0·8 p.f.) per extra kVA of demand	25s.	£5	£10
Corresponding p.f. penalty per kW per 0·1 p.f. reduction	4s. 6d.	18s.	36s.
Corresponding overall price per kWh on 25% load factor and 80% power factor	0·54d.	1·3d.	2·4d.

Table 4

DUTIES

Duty No.	Connection	F_h	Mean load during connection F_d	Overall load factor $F_l = F_d \times F_h$	Examples
1	Continuous	100%	70%	70%	Pumping and ventilating motors, booster and balancer sets
2	Factory hours	27·4%	70%	19·2%	Motors driving line shafting. Industrial machines in constant use on fairly steady loads
3	Factory hours	27·4%	35%	9·6%	Industrial machines in constant use on highly fluctuating loads
4	One-half of factory hours	13·7%	70%	9·6%	Individual-drive motors having only moderate use
5	One-quarter of factory hours	6·8%	70%	4·8%	Individual-drive motors where use only occasional
1A	Continuous	100%	35% at unity p.f. or 28% at 0·8 p.f.		Supply transformers

power factor (say 0·95 to 0·65) this is very nearly the same as a flat rate per unit change in power factor per kilowatt of demand. Thus in the case of the Grid tariff a charge of 4s. 6d. per annum per kW of demand is made for each 0·1 reduction in power factor below 0·85. This is approximately 15s. per annum per reactive kVA over the normal power-factor range, and this figure has therefore been used for the "cheap energy" price figures.

In the case of many l.v. power tariffs the power-factor penalty takes the form of a fixed charge per kVA of demand. In terms of reactive kVA this will produce a varying penalty depending on the particular consumer's power factor. Thus, with a fixed charge of £10 per annum per kVA of demand, the penalty per reactive kVA would be £3 at a power factor of 0·95, and £7 12s. at a power factor of 0·65. A uniform figure of £6 has been assumed for the "dear energy" figures, which will therefore represent roughly a plain kVA tariff when operating at a power factor of 0·8.* In the case of the medium-price energy an intermediate figure has been assumed.

(2.6) Duties

In Table 4, five sample duties have been selected for the motors and one for the transformers, representing load factors ranging from 70% to under 5%. In general the term "load factor" indicates the ratio of the mean load to the maximum load over a given period. As, however, these factors vary in kind as well as in degree, some further explanation is necessary. In what follows, the expression "maximum load" means the figure that would be recorded on a maximum-demand meter, i.e. the largest load (averaged over the integration period such as half an hour) which comes on to the machine once or oftener in each demand-assessment period. It is not concerned with any momentary or short-period loadings which may arise, nor does it necessarily coincide with the nominal full-load rating of the machine, although on the normal basis of selection it can generally be taken as coincident.

There are three load factors concerned in the problem, which may be defined as follows: The load factor during connection (F_d) is the ratio of the mean load averaged over the period of connection to the maximum load as defined above. The "hours" load factor F_h—sometimes called the "connected" load factor—is the ratio of the connected hours to the total hours, e.g. in the case of a yearly factor it is the hours of connection per annum divided by 8 760. The overall or total load factor (F_l) is the true factor, taking into account all sources of under-loading. Evidently $F_l = F_d \times F_h$. A reasonable assumption for factory working hours is 8 hours a day and 300 full days a year (e.g. 48 hours a week and 50 weeks a year). The "hours" load factor (F_h) is then equal to 27·4%.

There is yet another load factor, not quite in the line of these three, which is important in connection with diversity factor. This is the mean load during the factory hours (expressed as a ratio of the maximum load) and is referred to subsequently as the factory-hours load factor. It can be found by taking the overall load factor and multiplying it by the ratio which the total hours bear to the factory hours. It would coincide with the factor F_d, as defined above, in the case of a machine which was connected for the whole of the factory hours.

Whilst results are given for all five duties it may be useful to indicate which of them should be regarded as typical industrial service. From figures given in the Census of Production for the units consumed per horse-power installed it would appear that the average motor load factor is about 11% in the case of purchased electricity and 16% in the case of works generation, i.e. the average lies between Duty 2 and Duties 3 and 4.

(2.7) Fixed Cost and Diversity

The annual fixed cost of supply is the standing charge of the tariff, per kilowatt per annum, multiplied by the number of kilowatts of demand registered by the consumer's meter. When

* It will be appreciated that a charge of £6 per reactive kVA would be excessive if charged on the whole of this kVA, starting from unity p.f., but it is a representative figure for *changes* in kVA. The rate of change of lagging kVA with reactive kVA is equal to $\sin\phi$, which has a value 0·6 when $\cos\phi = 0{\cdot}8$. Since it is the cost of the *change* which is under consideration, a price of £6 per reactive kVA is the correct equivalent (at a working p.f. of 0·8) for a tariff which charges £10 per (lagging) kVA of demand.

Table 5

CAPITALIZED COST OF LOSSES (£)

I′ indicates the capitalized cost of 1 kW of series or copper loss
E′ indicates the capitalized cost of 1 kW of shunt or iron loss
R′ indicates the capitalized cost of 1 kVAr of magnetizing consumption

Duty No.		1	2	3	4	5	1A
Cheap energy	*I′*	76·3	41·8	23·4	25·4	15·7	35·3
	E′	122	59	59	38·6	26·2	122
	R′	8·85	8·85	8·85	6·7	5·07	8·85
Medium energy	*I′*	176	90	49	54	32·9	
	E′	286	130	130	83	55·3	
	R′	35·4	35·4	35·4	26·8	20·3	
Dear energy	*I′*	334	161	85·3	95·5	57·7	
	E′	548	236	236	148	97·2	
	R′	70·8	70·8	70·8	53·6	40·6	

These figures are only correct for "cheap" capital and 20-year life. For other lives and rates of interest multiply these figures by the factors given in Table 1. To find annual costs, divide by 11·8.

the machine in question is separately metered this demand reading will be the total full-load loss of the machine (constant and variable), and the same is true for collective metering when the machine is connected throughout the working hours of the factory and is on full load all the time it is connected. In all other cases there will be a diversity between the maximum demand of the machine and the maximum demand registered on the factory meter. This is because a machine which is only connected for 4 hours in an 8-hour factory day will only have a certain factor of probability of coming on to the factory peak.

It will further be evident that this diversity factor will be inversely related to the factory-hours load factor, although something less than a direct reciprocal. A machine connected 4 hours out of 8 is more likely to overlap the peak than one connected only 2 hours out of 8, but it will not be *twice* as likely. In the absence of data it is only possible to surmise, and then to embody the guess in an empirical relationship. A formula constructed by the author assumes a diversity factor of $(1/F)^m$, where F is the factory-hours load factor and m is a constant less than unity. In the paper m has been taken as 0·6 for the variable losses, and 0·4 for the constant losses and for the magnetizing consumption.

(2.8) Running Cost: Copper Losses and Load Factor

The running cost will be the annual kWh of loss consumption multiplied by the running charge of the tariff in pence per kWh. The loss consumption comprises the constant losses, at their full value for the period of connection, and the variable copper losses.

The annual value of the copper loss cannot be found merely from a knowledge of the load factor: the shape of the load curve must also be known. There are several ways of estimating this when a representative yearly curve is not available, and the subject has been fully discussed elsewhere.* Very briefly it may be said that when the actual load has an annual load factor of F, the load factor of the copper losses (i.e. the actual annual loss divided by what the loss would be if the full load were continuous) must lie between the two extremes F (as a maximum) and F^2 (as a minimum). A midway value has been found to be too high, and the value here assumed is $0{\cdot}3F + 0{\cdot}7F^2$. The value of F must of course be the load factor during connection (F_d).

As an example of the above it will be noted that Duties 3 and 4, although they have the same overall load factor, will not have the same copper loss. For since these losses are proportional to current squared, it follows that (for the same mean current) plant having a high load factor during connection and short hours of connection (Duty 4) will have higher copper losses than plant having a smaller current spread over a longer period (Duty 3).

(2.9) Cost of Losses

In order to show how the values in Table 5 are arrived at, it will be sufficient to work out a single comprehensive example. Consider for this purpose Duty 4, medium energy price, and take in the first place the cost of 1 kW of iron or other "shunt" loss (independent of loading). Connection is for half the factory hours, and so the diversity factor with the factory meter can be taken as $(1/0{\cdot}5)^{0{\cdot}4} = 1{\cdot}32$. The fixed charge at £6 p.a. per kW is therefore $6/1{\cdot}32 = 4{\cdot}54$. The running charge at 0·5d. per kWh is 4 (hours a day) × 300 (days a year) × $0{\cdot}5/240 = 2{\cdot}50$. Total cost for 1 kW of iron loss = 4·54 + 2·50 = £7·04 per annum, which can be capitalized by multiplying by 11·8, giving a total of £83.

Next consider the cost of 1 kW of "series" or copper loss (dependent on loading). The load factor during factory hours is $0{\cdot}5 \times 0{\cdot}7 = 0{\cdot}35$, so that the diversity factor can be taken as $(1/0{\cdot}35)^{0{\cdot}6} = 1{\cdot}88$. The fixed charge is therefore $6/1{\cdot}88 = 3{\cdot}19$. The load factor during connection is 0·7, and so the load factor of the losses can be taken as $0{\cdot}3 \times 0{\cdot}7 + 0{\cdot}7 \times 0{\cdot}7^2 = 0{\cdot}553$. The hours of connection are 4 × 300, and so the running charge is $0{\cdot}553 \times 4 \times 300 \times 0{\cdot}5/240 = 1{\cdot}38$. Total cost for 1 kW of copper loss = 3·19 + 1·38 = 4·57, which can be capitalized by multiplying by 11·8, giving a total of £54.

The cost of the magnetizing component follows the lines of the cost of the iron loss (fixed-charge portion only). At £3 per reactive kVA the cost is therefore $3/1{\cdot}32 = £2{\cdot}27$ per annum, which can be capitalized by multiplying by 11·8, giving a total of £26·8.

(2.10) Machine Losses: Effect of Changes in Rating

Table 6 shows the listed prices and consumptions for various ranges of motors and transformers. The figures are all expressed in the form $P = kH^n$, where H is the normal rated h.p. or MVA output. The figures for the motors are, it is believed, typical values for the period round about 1935, whilst the transformer figures are taken from a paper by C. W. Marshall.*

The effect of, say, a 1% change in output in the case of

* For a short bibliography and discussion of this point see D. J. BOLTON: *World Power*, 1932, 17, p. 12.

* "The Lower-Voltage Sections of the British Grid System," *Journal I.E.E.*, 1934, 74, p. 105.

Table 6

PLANT DATA

$P=kH^n$, where H=rated output in h.p. or MVA; and P=price in £, power loss in watts, or magnetizing consumption in VAr

Type	Speed (r.p.m.)	Range of sizes (h.p.)	Price		Copper loss		Iron loss		Magnetizing loss	
			k	n	k	n	k	n	k	n
Squirrel-cage	1 500	1 to 100	1·57	0·83	120	0·74	65	0·77	480	0·82
Squirrel-cage	1 000	1 to 100	2·4	0·75	106	0·79	55	0·80	660	0·78
Squirrel-cage	750	5 to 100	2·8	0·76	97	0·82	57	0·82	880	0·77
Slip-ring	1 500	5 to 100	3·2	0·72	130	0·74	61	0·76	630	0·78
Slip-ring	1 000	5 to 100	3·9	0·71	110	0·80	33	0·98	680	0·82
Slip-ring	750	5 to 100	5·3	0·66	120	0·78	42	0·92	870	0·81
D.C. shunt	1 500	1 to 50	3·5	0·73	92	0·74	160	0·50		
D.C. shunt	1 000	1 to 100	5·5	0·68	180	0·69	140	0·58		
D.C. shunt	750	1 to 100	7·1	0·66	160	0·73	85	0·70		
D.C. shunt	500	20 to 100	10·9	0·64	360	0·60	60	0·74		
		MVA								
Transformer, 33 kV on h.v. side ..		0·3 to 20	750	0·61	10 700	0·92	5 100	0·61	48 000	0·71
Transformer, 66 kV on h.v. side ..		2·5 to 45	1 380	0·45	7 380	1·03	5 420	0·69	53 600	0·70

normally rated machines can be calculated from this Table, using the formula $\delta P/P = n\delta H/H$.* The next step is to study departures from the standard ratings, i.e. the effect on the losses of changes in current and pressure loading.

The losses of an electrical machine can be placed in three groups, according to whether they are functions of the load current, the applied potential or neither. In symbols, losses $= aI^{\alpha} + bE^{\beta} + C$, where I and E are the current and voltage respectively. It will be sufficiently accurate to regard I (which here represents only the current through the series windings) as proportional to the output loading, and to regard the flux density in the core as proportional to the line voltage E. The components of the three groups are then as follows:

A. (Functions of I)—
- Series copper loss, $\alpha = 2 +$ † } Take as 2·1
- Stray load loss, $\alpha = ?$ } Take as 2·1
- Constant p.d. loss‡, $\alpha = 1$ } Take as 2·1

B (Functions of E)—
- Hysteresis loss, $\beta = 1{\cdot}6$ to $1{\cdot}8$ } Take as 1·9
- Eddy-current loss, $\beta = 2$ } Take as 1·9
- Shunt copper loss, $\beta = 2 +$ } Take as 1·9

C. (Independent)—
- Friction and windage

In considering the effect on the rated efficiency of under-running in either the I or E directions, only Groups A and B are considered. The reasons for neglecting any change in Group C (rotating machines) are given in the footnote to col. 2 of page 198. Further simplification is necessary if any practical results are to emerge, and in this paper the whole of Group A is taken as operating at an index of 2·1, and Group B at an index of 1·9. Such figures are necessarily compromise values, and in the former case the excess over 2 is purely empirical since the copper temperature-rise depends on several factors besides the current loading (e.g. the time element and the other losses). But since a sustained full-load temperature rise of, say, 50 deg C in the windings will mean a 20% increase in resistance, the effect (even if not calculable) is far from negligible.

Group A will be referred to in this paper as the "series" or "copper" losses (symbol I') and Group B as the "shunt" or "iron" losses (symbol E'). Should Group C losses require evaluation at any time they can be combined with Group B to form one group of "constant" losses, and the costs scheduled in Table 5 for the iron losses will apply without exception to the whole of these constant losses.

* See Section 1.8.

† The reason for this index differing from 2 is the positive temperature coefficient of the copper.

‡ For example, brush contact loss in commutator machines and electrode drop in rectifiers.

(2.11) Magnetizing-Consumption Changes

If a curve of magnetizing current is plotted against voltage for either an induction motor or a transformer it will follow roughly the shape of an ordinary B/H curve but with the ordinates interchanged. By drawing a tangent to the curve at the point corresponding to the normal voltage rating, the rate of change of current with voltage can be estimated. Unfortunately, at the flux densities usual in electrical plant (at, or slightly beyond, the knee of the B/H curve) this rate of change is both high and increasing rapidly. In a typical curve for Stalloy the slope was found to have halved for a 10% increase in flux density (the actual values for the reciprocal of the slope, H/B, being 2 at $B = 10\,000$ and over 4 at $B = 11\,000$ gauss).

For the motors, a number of curves of magnetizing current against voltage showed a slope of approximately 3 at the working point, and this would appear to correspond to a flux density of about 10 500 in Stalloy. This figure has been used throughout for the motors, and the rate of change of magnetizing current with voltage has been taken as three times the quotient (Normal magnetizing current)/(Normal voltage). That is:

$$\frac{\delta I}{I} = 3\frac{\delta B}{B} = 3\frac{\delta E}{E}$$

where I is the magnetizing current. Hence a 1% rise in voltage will produce a 3% rise in magnetizing current, and therefore a 4% rise in magnetizing kVA. For the transformers a rate of change of 5 has been taken (corresponding roughly to $B = 11\,500$ in Stalloy), so that a 1% rise in voltage will give a 6% rise in kVAr.

It is unfortunate that the consumption element which (on a power-factor tariff) has the largest effect on the cost is the one whose magnitude is hardest to estimate, and whose characteristics are rarely included in a quotation. It is time purchasers realized that data for the magnetization curve are just as important as a statement of the losses, and much more important than a statement of the price.

(2.12) Sample Motor Results

Table 7 shows the results in a single case, namely that of a 1 000-r.p.m. cage-rotor induction motor, with "cheap" capital and "medium" energy price. The figures express the economic advantage of under-running the copper and iron respectively,

Table 7

SAMPLE MOTOR RESULTS

Economic Advantage Ratio (in favour of under-running), 1 000-r.p.m. Cage-type, Medium Energy Price

	Copper ("*I*" direction)			Iron ("*E*" direction)					
	Without power-factor penalties			Without power-factor penalties			With power-factor penalties		
Size in h.p. ..	1	10	100	1	10	100	1	10	100
Duty No. 1 ..	6·6	7·1	7·5	1·4	1·8	2·2	44	47	50
Duty No. 2 ..	4·1	4·1	4·3	—	0·3	0·5	42	45	48
Duty No. 3 ..	0·9	0·6	0·6	1·7	2·4	2·7	43	47	50
Duty No. 4 ..	2·2	2·3	2·5	0·3	0·4	0·5	32	35	37
Duty No. 5 ..	1·2	1·3	1·4	0·3	0·4	0·5	24	26	28

Table 8

GENERAL RESULTS FOR 10-H.P. MOTORS AND TWO TRANSFORMERS: ECONOMIC ADVANTAGE RATIO (IN FAVOUR OF UNDER-RUNNING)

R.P.M. Type	Duty 1			Duty 2			Duty 3			Duty 4			Duty 5		
	Without p.f.p.		With p.f.p.	Without p.f.p.		With p.f.p.	Without p.f.p.		With p.f.p.	Without p.f.p.		With p.f.p.	Without p.f.p.		With p.f.p.
	Cu	Fe	Fe	Cu	Fe	Fe	Cu	Fe	Fe	Cu	Fe	Fe	Cu	Fe	Fe
Cheap energy															
1 500 Cage	3·7	1·8	12	2·3	0·6	11	0·4	1·6	12	1·3	0·5	8·1	0·7	0·4	6·2
1 000 Cage	3·1	0·7	12	1·9	0·10	11	0·4	1·0	12	1·1	0·16	8·7	0·6	0·19	6·6
750 Cage	2·0	0·8	13	1·3	0·16	12	—	1·0	13	0·7	0·18	9·4	0·4	0·2	7·1
1 500 Wound	3·4	0·7	9·6	2·1	0·12	9·1	0·6	0·9	9·9	1·2	0·16	6·9	0·7	0·18	5·3
1 000 Wound	2·2	—	8·4	1·4	—	8·5	0·2	0·3	9·2	0·8	—	6·5	0·4	—	5·0
750 Wound	2·1	—	9·5	1·3	—	9·4	0·2	0·4	10	0·7	—	7·2	0·4	0·01	5·5
1 500 D.C.	1·6	4·2		1·0	1·9		0·09	2·4		0·6	1·3		0·3	0·9	
1 000 D.C.	3·2	2·2		1·9	0·8		0·6	1·5		1·1	0·6		0·6	0·5	
750 D.C.	2·2	1·3		1·3	0·5		0·3	1·1		0·8	0·4		0·4	0·3	
500 D.C.	4·4	—		2·5	—		1·2	0·1		1·5	—		0·9	—	
Medium energy															
1 500 Cage	8·3	4·4	45	4·8	1·4	42	0·6	3·7	44	2·7	1·1	32	1·5	0·9	24
750 Cage	4·6	2·0	50	2·7	0·5	49	—	2·2	51	1·5	0·4	37	0·8	0·4	28
1 500 Wound	7·8	2·1	38	4·3	0·4	36	1·1	2·2	38	2·5	0·4	27	1·4	0·4	21
1 000 Wound	5·0	—	35	2·9	—	35	0·3	0·7	36	1·6	—	27	0·8	—	20
750 Wound	4·7	—	38	2·8	—	38	0·3	1·0	39	1·6	—	29	0·9	0·02	22
1 500 D.C.	3·5	9·8		2·1	4·2		0·07	5·3		1·2	2·8		0·6	1·9	
1 000 D.C.	7·3	5·2		4·0	2·0		1·2	3·4		2·3	1·4		1·3	1·1	
750 D.C.	4·9	3·2		2·8	1·2		0·5	2·4		1·6	0·8		0·9	0·7	
500 D.C.	10·2	—		5·3	—		2·4	0·2		3·1	—		1·9	—	
Dear energy															
1 500 Cage	16	8·5	90	8·5	2·7	84	0·7	7·0	88	4·7	2·7	64	2·6	1·6	48
1 000 Cage	13	3·7	93	7·2	0·7	90	0·7	4·6	94	4·0	—	65	2·2	0·7	52
750 Cage	8·6	3·8	100	4·8	1·0	98	—	4·2	101	2·7	0·8	74	1·4	0·7	56
1 500 Wound	15	3·6	73	7·7	0·8	70	1·6	4·1	73	4·4	0·7	55	2·5	0·7	42
1 000 Wound	9·4	—	70	5·1	—	70	0·3	1·5	86	2·8	—	53	1·6	—	41
750 Wound	9·0	—	77	4·9	—	76	0·4	2·0	79	2·7	—	58	1·5	0·04	44
1 500 D.C.	6·7	19		3·7	7·7		—	9·8		2·1	5·0		1·0	3·4	
1 000 D.C.	14	10		7·1	3·8		1·8	6·4		4·1	2·6		2·3	1·8	
750 D.C.	9·3	6·2		5·0	2·2		0·7	4·5		2·8	1·5		1·6	1·2	
500 D.C.	19·2	—		9·5	—		4·1	0·6		5·6	—		3·3	—	

SUPPLY TRANSFORMERS, DUTY 1A, CHEAP ENERGY

	Copper	Iron
2 MVA, 33 kV	—	6·1
10 MVA, 66 kV	—	7·8

first when the tariff does not include power-factor penalties and secondly when it does. In the latter case there is never any advantage in under-running the copper, and no values are given for this. (As before, a fractional value indicates a ratio in favour of over-running.) Figures are given for three different sizes, namely 1, 10 and 100 h.p., and the conclusions can be summarized as follows.

On all duties, if there is a power-factor penalty the iron should be under-run and the copper should be over-run, very far from the existing densities. If there are no such penalties then on heavy duties (1, 2 and, to a less extent, 4) the copper should be under-run. On other duties the present copper ratings are approximately correct. As regards the iron, when there are no power-factor penalties this should be over-run on Duties 2, 4 and 5 and under-run on the other two; but in none of these cases are the ratios very high, and so present ratings are reasonably economic.

Comparing different sizes, the larger ones showed slightly increased ratios in favour of under-running or decreased ratios in favour of over-running. This effect, however, was peculiar to this particular range, and probably due to the fact that the price index (0·75) was smaller than the loss indices. For example, in the case of the 1 500-r.p.m. motor of the same type the effect of larger sizes was in general the reverse of the above. On the whole, size had comparatively little effect, and the economic advantage ratio was fairly similar throughout the range from 1 to 100 h.p. The variation was not thought sufficient to justify the space required for full tabulation, and so in Table 8 the figures refer to 10 h.p. in every case.

(2.13) General Results and Conclusions

Table 8 shows the general results for the motors (10-h.p. size) and for two sizes of transformer, the latter being large 3-phase units on supply duty. The conclusions for the motors are similar to those already stated, with the addition that the advantage ratio for under-running increases with the energy price. With the d.c. motors, there is a high ratio in favour of under-running these (except the low-speed ones) in the voltage direction, in all but light-duty and cheap-energy situations. Under-running the copper is only advantageous when the energy is dear or the duty heavy. In the case of the transformers it is clear that the present flux densities are economically too high and the current densities too low (i.e. the same as for the induction motors on p.f. tariffs). Economically the transformer copper is at present (on low tariffs) under-run, and the iron is grossly over-run.

The very large ratios all occur in respect of voltage under-running when there are p.f. penalties, and it may be urged that in such cases it would be more economical to reduce the reactive consumption by installing condensers, etc., than to buy larger induction motors or transformers. That is true whenever the tariff is more than £2 or £3 per kVA, and it was for this reason that the results have been classified according as they were obtained with or without p.f. penalties. The latter apply where either the tariff neglects power factor or condensers are used to supply the magnetizing component. It must be remembered, however, that in spite of all the efforts of the interested parties there are still many thousands of horse-power of uncorrected induction motors on kVA tariffs. Moreover, even at so low a price as the Grid penalty of 4s. 6d. p.a. per 0·1 p.f. ("cheap" energy) there is frequently a great gain in voltage under-running.

Before concluding, some mention should be made of other factors. In addition to the obvious economic elements of plant and energy cost there are several items not easily evaluated in £ s. d. which should be taken into consideration. Thus, high flux-densities have a bad effect on the system operation owing to harmonics; they increase noise in transformers and complicate parallel running. Other items affected by economic size selection are the following: heat dissipation, particularly in situations requiring totally-enclosed motors; overload capacity; the power absorbed by external cooling devices; the cost of heat-dissipating plant (e.g. tank size and oil quantity in transformers); effect of working temperatures on life of plant. Almost all these omitted items would have the effect of strengthening the case for under-running.

(2.14) Effect of Changes in Data

Each of the figures in Tables 7 and 8 is a ratio between cost of losses and cost of plant, both reckoned on a common basis depending on the life estimate and the rates of interest. Assuming no change in the life estimate, and using the term "capital rate" to indicate the combined charge for interest and depreciation (8·47% in this case), the tabled figure depends upon

$$\frac{\text{Price of supply}}{\text{First cost of plant} \times \text{Capital rate}}$$

From this can be calculated the correction factor corresponding to any change in data.

Thus for induction motors the increase in price from the figures in the paper up to those prevailing at the beginning of the war was about 35%. (The d.c. prices had increased by twice this figure.) Hence with a tariff of, say, £7 per kW plus 0·6d. (= "medium" supply price multiplied by 7/6 approximately) and a capital rate of 9% the correction factor would be

$$\frac{7/6}{1{\cdot}35 \times 9/8{\cdot}47} = 0{\cdot}81$$

It follows that each of the economic advantage ratios given in Tables 7 and 8 must be multiplied by 0·8 in order to be correct for the new data.

(2.15) Action and Attitude

There are various ways in which the conclusions of this paper can be implemented. In the first place, there is endless scope for individual action by purchasers, whether operating on their own initiative or on the advice of consultants and contractors. In every quotation, instead of being satisfied with the usual data as to efficiency and power factor, the following four separate items of information should be called for: copper loss, constant loss, magnetizing consumption (or power factor, if induction motor), and percentage change in magnetizing current for a 1% change in voltage. Armed with these data and some knowledge of the working conditions (hours and tariff) it will be easy to find when the losses cost bears a high ratio to the plant cost, and fairly easy to calculate whether the next larger size of motor or transformer, suitably under-run, will be substantially cheaper.

Unfortunately the calculations will hardly appear simple to the non-technical power user. Moreover, the small-scale purchaser frequently does not consult a disinterested expert but relies upon the free advice bureau furnished by the manufacturer's technical data. Much therefore depends upon the plant manufacturers.

It would be unfair to ask for a change of heart on the part of the manufacturer and designer. The motive power can only come from the purchaser, who must demand a higher-efficiency article and be willing to pay more for it. But it is legitimate to plead for a certain change of mind and attitude on the part of the maker, so that the drive when it comes shall be intelligently directed. The machine losses must come to be regarded not merely as a temporary inconvenience to the designer who has to dissipate them, but rather as a permanent liability to the user who has to pay for them.

A perfect example of wrong thinking can be seen in the current attitude to fans on rotating machines. Time was when a fan

on an electric motor was a special device to overcome abnormal difficulties, but it has now become an integral element in motor design, and the manufacturers assure us that fans save money—though *whose* money is not so clear. It is economically very short-sighted to suppose that this change has been for the better. The truth of the matter can best be expressed by saying that to meet an energy loss by fitting a fan is like treating bad drains with eau-de-Cologne. Actually the case is worse than this, for the fan aggravates the disease whilst effectually masking the symptoms. Temperature rise is merely the symptom of a disease known as energy loss; and to provide paths for easy dissipation, whilst it may be a convenient and necessary palliative, does nothing to cure the trouble. The real trouble, in a word, is the *cost* of supplying this energy, not the difficulty of dissipating it.

One way in which manufacturers might help would be by tendering alternative machines, one complying with B.S.I. requirements at a competitive figure and the other at a higher price with certain guaranteed maximum-loss figures. A note could indicate how these would prove economic wherever the duty was not exceptionally light or the energy price low.

Apart from selection by individual purchasers or publicity by manufacturers, there is some room for collective action. Even if it is impracticable to include efficiency in a specification it should be feasible to indicate what are the three or four loss-consumptions that should be asked for in a quotation; and possibly to give some idea of the percentages above which it is uneconomic for these to rise, in a situation of average energy price and degree of utilization.

PAPER No. 2: THE ECONOMIC FLUX DENSITY IN LARGE SUPPLY TRANSFORMERS*

SUMMARY

Technical developments may at any time make it possible to increase the working densities in our electrical machines, and so enable a larger output to be obtained from a given frame-size and weight of active materials. This paper assumes that an increase of transformer flux density is technically feasible, and tries to discover whether it is economically desirable. Only a single situation, and only two (fairly large) sizes of transformer such as would be used on the lower-voltage sections of the Grid, are examined. The results are emphatically against any such increase, and in favour of lower densities than those in use at present.

The economics of higher-grade steel is briefly examined.

(1) INTRODUCTION

There have been several inquiries into the feasibility of increasing our present transformer flux densities, either with the existing materials, by using better-quality steel, or by making use of magnetically oriented laminations. In general, the economics of the change has been disregarded, except on that short-term view which may be called "first cost economics." It has been tacitly assumed that if the same output can be obtained from a smaller quantity of active materials, and if most of the saving is passed on in the transformer price, the result will be a gain to all concerned. Since, however, the user has to pay for the losses as well as for the transformer, an increase in the former may well obliterate any gain on the latter.

The simplest way of studying the point is to postulate the possibility of some such change and then to examine the consequences. The following calculation supposes that it is possible to increase present flux densities by 10%, and it endeavours to see whether there will be any overall gain in reducing the plant cost in this way. If the answer is a decided negative, the contrary action must be contemplated in the shape of greater plant expenditure, either on lower densities or on higher-grade steel.

(2) METHOD

The method of comparison is briefly as follows: Starting with a normally-rated transformer (A) of some particular size the total costs of purchase and operation are evaluated on a common basis, in this case capitalized costs. The same size of frame is then presumed to be run with 10% higher flux density (Transformer A′). The result will be a 10% increase in output, approximately 19% increase in iron loss and a very considerable rise in magnetizing consumption.

It might appear that the market value of the 10% extra output could be obtained by examining a range of normally-rated transformers of the type A, and seeing how the price goes up with output. (In practice a 10% greater output would mean about 6% more in first cost.) This increase in first-cost value estimated from A could then be balanced against the cost of the extra iron losses and magnetizing component estimated from A′. There is, however, a certain flaw in this argument, because a larger output when obtained by the normal means of a larger transformer would be accompanied by a larger copper loss, whereas the over-run transformer obtains the extra output without any increase in copper loss. It is therefore necessary to make an overall comparison, including copper loss as well as iron loss, between the over-run transformer A′ and a larger-frame-size normally-run transformer B giving the same output.

Time is saved and a greater accuracy obtained by dealing only with the cost differences, i.e. by omitting all the values relating to the original transformer A and therefore common to both alternatives. The final stage of the calculation then shows the *extra* cost of obtaining 10% greater output by two different methods, namely A′ using the original frame-size but over-running the iron, and B using 10% larger frame-size, normally-rated.

(3) DATA AND CALCULATIONS

Table 1 shows the assumptions made and the constants derived therefrom. Table 2 shows the complete calculation set out in four stages, and the following are references to the numbered lines.

Lines 1 to 6 embody the transformer data, which are taken from C. W. Marshall's paper "Lower-Voltage Sections of the

Table 1

ASSUMPTIONS AND CONSTANTS

Assumed data:

- Life: 20 years and zero salvage value (or 18½ years with salvage value = 10% of first cost)
- Interest: 5% on loan and 3½% on reserve fund (or 5¼% if single rate)
- Price of supply: Standing charge per annum per kilowatt = £3 + 4s. 6d. per 0·1 of power factor below 0·85
- Running charge per kWh = 0·2d.
- Duty: Continuous connection, 28% load factor at 0·8 power factor

*Constants calculated therefrom.**

- Present worth of £1 per annum over life period: £11·8
- Capitalized cost of 1 kW of full-load copper loss: £35·3
- Capitalized cost of 1 kW of iron loss: £122
- Capitalized cost of 1 kVAr of magnetizing consumption: £8·85

* See Paper No. 1, p. 195.

* Though the two papers have been run together for reasons of economy each is complete in itself and can be consided without the other. The relation between them is that whilst they cover similar ground, Paper No. 1 makes a precise and detailed study based on the hypothesis of small (1%) changes. Paper No. 2 is simpler and more tangible because it is confined to a single question and it presupposes bigger changes.

Table 2

CALCULATIONS AND RESULTS

			66 kV	33 kV
Transformer A (original).				
1	Rated output	MVA	15	2·5
2	First cost	£	4 305	1 280
3	Copper loss at full load	kW	139	24
4	Iron loss	kW	29·25	8
5	Magnetizing consumption	kVAr	319	69
6	B_{max} in core and yoke	kilogauss	13·9/12·1	12·6/10·0
7	B_{max}: effective mean value (assumed)	kilogauss	13·0	11·3
Transformer A′ (over-excited to have 10% greater density and output).				
8	Iron loss, Line 4 × $1·1^{1·9}$	kW	35·06	9·59
9	B_{max}: effective mean value, Line 7 × 1·1	kilogauss	14·1	12·4
10	H corresponding to Lines 7 and 9		21/36·5	11/16·2
11	Magnetizing consumption: Line 5 × 1·1 × ratio in Line 10	kVAr	610	112
Transformer B (larger frame-size, to give 10% greater output).				
12	First cost, Line 2 × $1·1^{0·45}$ or $1·1^{0·61}$	£	4 494	1 357
13	Copper loss: Line 3 × $1·1^{1·03}$ or $1·1^{0·92}$	kW	153·3	26·2
14	Iron loss: Line 4 × $1·1^{0·69}$ or $1·1^{0·61}$	kW	31·24	8·48
15	Magnetizing consumption: Line 5 × $1·1^{0·70}$ or $1·1^{0·71}$	kVAr	341	73·8
Cost differences.				
16	Iron loss, A′ over B (Line 8 — Line 14) × 122	£	466	135
17	Magnetizing loss, A′ over B (Line 11 — Line 15) × 8·85	£	2 380	336
18	*Less* copper loss, B over A′ (Line 13 — Line 3) × 35·3	£	507	78
19	Total losses cost excess, A′ over B (Line 16 + Line 17 — Line 18)	£	2 339	393
20	First cost excess, B over A (Line 12 — Line 2)	£	189	77
21	Economic disadvantage in over-running, Line 19 ÷ Line 20		12·4	5·1

Grid.”* Two sizes are selected, one from the middle of each range (66 kV and 33 kV). The flux densities listed for the yoke are some 5% to 20% less than those for the core, and for the purpose of estimating the magnetizing-current increase an effective value for B_{max} has been taken midway between the two (Line 7). This is obviously a considerable under-statement of the case, for even if there were approximately equal weights of iron operating at the two densities the bending-over of the B/H curve means that the higher density would exert a disproportionate effect upon the magnetizing current. It should be remarked that, whilst the 66-kV transformer has an average flux density for its range, the 33-kV transformer has a density below the average.

The next section of the Table shows the effect of running the same size of transformer with 10% higher flux density (Line 9). This could be effected either by re-design or by over-running the iron whilst keeping the copper unchanged (e.g. if a standard transformer were ordered for 60 kV and then run on 66 kV). The latter assumption is made here, and the iron loss is taken as proportional to $B^{1·9}$ (Line 8).† In order to find the probable increase in magnetizing current a B/H curve for Stalloy was consulted, and values of H were taken for the two values of B (Line 10). The magnetizing consumption was then increased in this ratio (for the current increase) multiplied by 1·1 (for the voltage increase).

The third stage is to find the price and losses of a larger frame-size transformer (B) capable of giving the bigger output at the original flux density. It might be thought that these data could be obtained from the original range of transformers, but two factors prevent this. In the first place, the outputs listed go up in jumps of 20% to 50%, whereas the increase postulated here is only 10%. In the second place, although the listed prices and losses when plotted against output follow tolerably smooth curves, individual sizes are always liable to depart from this mean line owing to the exigencies of design and the particular maker's standards of frames and punchings. (Provision of tap-changing gear also caused a break in the 33-kV curve.) Hence a comparison between two transformers in the range might give very misleading results if they happened to vary from the mean in opposite directions.

In the present case a single transformer in the range A has been taken as the starting point, and Transformer B has been “projected” from A by using the slopes of the mean curves for the range. (By plotting price against kVA from Marshall's paper the index was found to be 0·45 in the 66-kV range, and 0·61 in the 33-kV range. Similar indices, as shown, were found for the copper loss, iron loss and magnetizing consumption). Since the economic calculation is based on the cost differences, any abnormalities in A will not affect the result.*

The last portion of the Table shows the economic calculations in the form of the excess cost, first of A′ over B and then of B over A′. It will be noted that the over-run transformer (A′) has the larger iron loss and magnetizing consumption, but its copper loss will be as initially since the windings and current densities are unaltered. Transformer B, although presumably working at the same current density, will have a larger copper loss because it is a bigger machine; and this must be deducted (Line 18) in order to get the relevant total. Each of these loss differences is converted into its capital equivalent by multiplying it by the appropriate figure from Table 1. The net total is then compared with the greater first cost of B over A.

(4) RESULTS

The results (Line 21) show that in the case of the 15-MVA 66-kV transformer, over-running the iron by 10% would cost in losses 12½ times as much as it would save in value of increased plant capacity. (Another way of putting it is to say that the extra consumption costs as much *every year* as the reduction effected in the first cost.) Conversely, a reduction in flux density would save many times more than it cost. It would not be true,

* *Journal I.E.E.*, 1934, 74, p. 105.

† The normal iron loss is taken as the fixed loss at half load, i.e. omitting the power required to operate the external cooling devices.

* This does not necessarily give the actual manufacturing cost of building Transformer B in any given instance, which would depend on a number of extraneous factors such as how the particular output fitted in with existing manufacturing standards. It does, however, give the *mean* manufacturing cost of such an increase, occurring at any point in the range.

however, to say that under-running the iron would save money in so high a ratio as $12\frac{1}{2}$: 1, since the rates of change, particularly of the magnetizing current, are not constant over a 10% variation.*

In the case of the 2·5-MVA 33-kV transformer the ratio against over-running is only 5, owing to the low initial density on this size. This made the normal iron loss small in proportion to the size, so that the cost of a given increase in this loss was relatively small. The normal magnetizing consumption was likewise small, and the cost on this score of a density increase was low for two reasons—the small initial value and less flatness in the B/H curve. The calculations confirm what would be expected, namely that when the initial density is high an increase will be expensive in iron loss and still more expensive in magnetizing consumption.

(5) CONTRARY ACTION

Although the chief purpose of this paper has been to demonstrate the economic disadvantage of an increase in flux density the matter can hardly be left where it is, merely as a simple negative. The figures show only too clearly that the existing densities are far from being the optimum values, and it is natural to ask what these optimum values are. Since the various curves of costs and losses cannot suddenly change their shape, it is clear that, if a moderate increase in density costs 12 times what it saves, a small decrease will save many times what it costs. A substantially lower flux density would undoubtedly be economic for the user, and the question is—how much lower, and where is the process to stop?

In the matter of magnetizing current, the curve changes shape very rapidly in the region of 12 to 14 kilogauss, and when the flux density is reduced below this figure the rate of change is much less. The same remarks, but to a less extent, apply to the iron loss, with a net result that an economic ratio of $12\frac{1}{2}$: 1 against density increase when the normal density is 13 kilogauss becomes only 5 :.1 when the normal density is 11·3 kilogauss (2·5-MVA size).

Taking the transformer with the lowest normal density in Marshall's list, namely the 4-MVA 33-kV size (effective density 10·75 kilogauss), the economic disadvantage of density increase was found to be only 1·5 : 1 (calculation not listed here). Slightly below this point the ratio would evidently be unity, and the optimum density would be reached. At such a point, a small change in density in either direction would save just what it cost, and this is the economically correct density for the set of conditions specified.

(6) QUALITY OF STEEL

The technique of economic choice developed in the accompanying paper, and illustrated in the present one can be applied to any change, either quantitative or qualitative, in any of the active materials of an electrical machine. The question has recently been raised regarding the *quality* of transformer steel, and this (like the question of density) is of immediate economic interest to the purchaser.

Rough figures may be given for the 15-MVA 66-kV transformer already worked upon. The iron loss is 29·25 kW, and assuming a loss of 1 watt per lb for 14-mil sheet with $B_{max} = 13$ kilogauss this indicates 29 250 lb of active iron. At a pre-war price of £30 per ton this iron would cost £392. If by some means the quality could be improved merely to the extent of reducing the iron loss and magnetizing consumption by 10%, the reduction on the above-mentioned tariff would save the user £54 per annum, or a capitalized value of £638, i.e. 60% more than the whole cost of the iron. It follows that even if the better-quality material cost double, and the extra were all passed on to the purchaser of the transformer, the latter would still be considerably better off than at present.

(7) CONCLUSION

In estimating the economic disadvantage of over-running, or advantage of under-running, no credit has been taken for any of the incidental gains arising from lower flux densities. These include less noise, less disturbance from harmonics and therefore easier parallel running, smaller tanks, less oil and less power absorbed by heat-dissipating gear. In addition, the lower working temperatures are likely to increase the life and the overload capacity.

Finally, it may be pointed out that if a smaller situation had been visualized instead of the bulk-supply service examined in this paper, a still more striking result would have been obtained. It is true that a change in size *per se* will probably not have much effect on the economic calculation. A smaller transformer will cost more per kVA and will have bigger losses per kVA, so that these two effects will tend to cancel out. But a smaller size will almost always be associated with a higher supply price, and here one is faced with very substantial variations. The cost of l.v. energy as distributed to the user will seldom be less than twice the Grid tariff worked on above, and this will very greatly strengthen the case for economic selection.

In the case of a works transformer which is only connected for a few hours each day it might be thought that the iron loss and magnetizing consumption would be relatively unimportant. But when the tariff is of a two-part character, especially if there are power-factor penalties and the transformer is in circuit at the time of the factory peak, the cost of the fixed losses will be very considerable. Thus at £5 per kVA of demand the cost of a change in iron loss and magnetizing current will be very much greater on the standing charge alone than it was on the Grid tariff, counting both standing and running charges. This cost will apply however little the transformer is used, provided the use overlaps the peak period.

DISCUSSION BEFORE THE INSTITUTION, 2ND DECEMBER, 1943

Mr. C. W. Marshall: I am most interested in the second of these papers, and particularly in the quality of transformer iron. On the question of economic flux density, the author shows that the optimum value should be of the order of 10·75 kilogauss for a 4-MVA 33-kV unit. The accuracy of his conclusions depends on the reliability of the basic data of Table 1, but otherwise his conclusions are factual and not speculative. In the original specifications for the Grid transformers, the value of a kilowatt of fixed loss was assessed at £45, but under present-day conditions the corresponding figure would be £107, which is of the same order as that used by the author. The exact economic effect of flux-density changes can be determined only if the copper losses are known. These are difficult to estimate over a long period for the Grid transformers, since the loading of these transformers depends more on the efficiency of the power-station plant and on the availability of that plant than on the transformer characteristics, which are economically insignificant. I am not suggesting that this is an adequate reason why they should not be specially examined.

In pre-war days, the Central Electricity Board adopted a flux density of 11 kilogauss, mainly with the object of cutting out harmonic and noise difficulties. As the harmonic difficulties express themselves in whistling noises from inductive circuits, such as house-service-meter voltage coils, radio interference and overloading of power-factor-correcting capacitors, and affect a

* A ratio of nearly 8 : 1 is suggested by the results given in Paper No. 1.

large number of individual consumers, the desirable method of tackling the difficulty is at the source rather than by modifying consumers' apparatus. Noise does not often cause nuisance; nevertheless, in the general interest it should always be kept at a minimum, and again low flux density is a definite help. During the war, we have had for obvious reasons to work with much higher flux densities than formerly.

The insistence on low flux density recalls German practice introduced just before the war, whereby extremely high flux densities were used—16 kilogauss certainly, and possibly 18 kilogauss on very large transformers. The German designers succeeded in keeping the wave form fairly sinusoidal; if power losses and noise emission were also kept reasonably low this was a notable contribution to transformer progress, and one well worth examining.

So far as the quality of transformer iron is concerned, there can be no question that improvement is desirable. The author quotes only one figure in his second paper for specific losses, namely 1 W loss/lb for 14-mil sheet at 13 kilogauss and 50 c/s. For convenience, it seems preferable to concentrate on the standard figures of loss for a density of 10 kilogauss, and these, for British iron, range from 0·63 down to about 0·49 W/lb; the better-quality iron is not very easily obtained. I have good reason to believe that foreign manufacturers have produced iron with a specific loss as low as 0·35 W/lb, and it seems essential for our transformer manufacturers to have such iron available if they are to compete successfully abroad. In this connection, it should be recalled that all the major fundamental developments in improving electrical sheet iron have been made by British scientists and steel manufacturers.

It may be of interest to give authentic figures for some larger transformers than the author has considered, and I have here some figures relating to a 30-MVA, 132-kV unit. Its cost was £16 400, which is £0·547 per kVA. The iron losses were 60 kW, the copper losses 260 kW at full load, and the cooling pump and fan losses 19 kW. Taking the cost of losses at £3 per kW and 0·2d. per kWh, at 100% power factor the total charges for iron are £618, for copper £2 678 and for cooler £196, making £3 492 in all. I have taken no account of magnetizing consumption costs, because the magnetizing effects have a useful function in compensating for excessive capacitance currents, which are sometimes a trouble when the power load is light.

Finally, I suggest that every large transformer is worthy of proper metering equipment to determine the throughput of power and energy. That can easily be done by having integrating meters on the low-voltage side; it would be better still if loss meters could be added. These have been partially developed and justify complete development, because, in addition to showing up accurately what the economics of a particular purchase are, they provide a guide as to whether the transformer magnetic circuit is deteriorating.

Mr. D. B. Hoseason: The author infers that our designs are focused essentially on technical characteristics, and that designers take very little interest in the economic side of the question. This is not so in most design departments, and a good many papers on design matters have been read before The Institution in which economics has been emphasized.

I disagree with the author's conclusions because I think that his premises are incomplete, and as a result his conclusions misleading. In the first place, the cost of a 25% larger motor or transformer is not merely the extra cost involved in the manufacturer's selling price. Other increases in charges have also to be taken into account, such as higher insurance premiums, rent and rates and more provision for spares, overhauls and replacements, etc. These factors will not alter the conclusions for the continuous-duty motor, but for the general-purpose industrial motor in groups 2, 3 and 4 the position is nothing like so favourable towards under-running as the paper indicates.

My second criticism is centred on the figure of a 20-years' life. Any good motor manufacturer will produce equipment which will last 20 years or more, but the question is, how long is the user going to employ the motor? Many of these small machines, especially motors below 50 h.p., are used in the secondary industries, and the user has by no means 20 years' expected life for a 10-h.p. or 20-h.p. motor. It is much more likely to be some 6 or 8 years, when the particular driven machine will probably become obsolete. The 10-h.p. motor will go into the factory stores, perhaps for two or three years, or it will be sold second-hand for only 40% of its new value, while still perfectly sound. In dealing with small machines in particular, therefore, the economist must bear in mind all industrial conditions ruling, and not the possible technical life which the designers can give the machine.

A final point which is debatable is the approach to the problem from the standpoint of unlimited capital resources. This attitude does not represent the conditions under which a company or a corporation operates. A limited amount of capital is usually borrowed at rates of interest of the order indicated by the author, but it almost invariably pays to make this capital handle the greatest possible output of finished goods, i.e. the key to the problem is earning power rather than interest on loan. The difference between earning power and interest on loan has an immense influence on the subject and on applying in Table 8, not interest on loan capital but the earning power of the money borrowed, the results are completely changed. In fact, the figures then support the best practice of present-day motor manufacturers.

Sir Frank Gill: I wonder whether the author's final words infer that one should not worry about anything but the lowest first cost? He could not have meant that. More investigations into economic matters are needed, and this will compel the teaching of economics in universities and schools.

There are several new terms in this paper, such as "price" and "plant cost" applied to the same thing and meaning first cost. The word "price" suggests the price from the maker, whereas "first cost" includes everything that goes to put the thing in place and ready to work. Probably "price" is just as good a term if it is known what is meant, but other words are in use. It is helpful not to coin more new terms than are actually needed. If we must coin words, the young engineer should not talk to the business man in what is described as engineering jargon; let him talk in the business man's language.

In Section 2.1 of the first paper, where the author says "quarterly payments being assumed for all items," have not the words "sinking fund" been omitted and should not the text read "quarterly payments being assumed for all sinking fund items"?

Assuming that Tables 7 and 8 are correct, they seem to indicate many openings for intelligent selection, and that is one of the most important points about engineering economics; from alternatives the technical method is selected which will do the job at the lowest cost. Under war conditions this may not be possible, but it will be possible again later. If an economic advantage rate is as good as appears in the tables, does that indicate that there is something wrong with a tariff which allows an ingenious selector to avoid the payment he would otherwise have to make?

Is it quite certain that economics are sufficiently considered in our Standard Specifications? In the fan case the author appears to say that although losses are kept down by cooling, the cost of doing so does not enter into consideration. On the other hand, in the recent Order the instructions are to keep up the losses in transformers and motors in order to save materials. Presumably materials include fuel (a rather rare material at the

present time). If so, this is a good example of economics entering into Standard Specifications.

Mr. R. M. Charley: It may appear that a recent Statutory Order, S.R. and O. 1353, is the negation of the principle advocated by the author, but it must be remembered the order was an emergency measure dictated by war conditions, and although it precludes the application of the author's ideas at present, there are other valuable features which I hope will be adopted by users and manufacturers alike as a permanent measure.

The problem of determining what is the most economical transformer involves several factors, including, of course, the relative costs of copper and steel. Unfortunately, in recent years the latter factors have not increased in cost by a like amount, copper having increased by 27% and transformer steel by 60%. Consequently, the most economical design in 1939 is not the best to-day.

The author's figures for capital cost of transformers are not in accord with present-day prices. I consider that the 2·5-MVA 33-kV transformer would have on-load tap-changing equipment, in which case the price to-day would be about £2 800. This fact does not materially affect the author's conclusion, and I would strongly support the view that his principle is equally justifiable when applied to small distribution transformers. The total capacity of transformers supplied from the l.v. side of the 2·5-MVA bulk-supply unit may be 4 900 kVA: the iron losses would be 8 and 34 kW respectively; hence there is every incentive to reduce the loss of the distribution units. It may be argued that the cost of these smaller units is so much greater; this is true, and the 4 900 kVA unit would cost about £10 000. On the other hand, it costs less to reduce the iron loss in a small transformer than in a big one, and furthermore the tariff charge on which the loss would be capitalized is likely to be greater than for the bulk-supply unit. Hence, I believe that when the restriction on the use of steel is removed the principle advocated by the author should become general practice.

I venture to offer a word of warning. Tappings are usually provided on the h.v. winding to allow for variations in the supply voltage, not to enable the low voltage to be increased. If the latter practice is adopted the result is an increase of flux density, and hence the value of the saving in iron loss by reduction of flux density is largely vitiated.

The author suggests that copper loss must not be neglected: I agree, particularly on small transformers, not so much on the value of the loss, but on account of regulation. In small transformers the reactance is low and the copper loss high: the power factor of the load is usually very high. The formula for regulation at unity power factor is (Percentage copper loss) plus (Percentage reactance)^2/200. Hence a saving in copper loss means an improvement in voltage regulation with an ultimate increase in revenue.

There has been little betterment in the quality of transformer steel for a number of years, and English transformers have not been competitive in the world market in respect to iron loss. I consider it is high time that steel suppliers in this country offered to the transformer makers steel of a much better quality than has been available in the past, so that immediately after the war we shall be able to compete effectively in the world market.

Mr. E. T. Norris: The essence of these papers is to be found in the two statements, (*a*) and (*b*), in Section 1.3 of the first paper, and these might well have been included in the conclusions.

In my view, capitalization is not so new or as uncommon as the author suggests. So far as transformers are concerned, the majority of transformer purchasers and users in this country do appreciate the value of, and have worked out, the most suitable capitalization values. But it is rare to find users with the courage of their convictions. In consequence, rather than discussing merely capitalization values, it seems more important to study the limitations of their application, and determine why, when users have decided what their losses are worth to them, they so often do not apply the result rigorously.

To my mind, the most striking feature of the papers is the extraordinary values which the author obtains for power-factor penalties. These charges greatly affect his conclusions, in some cases to several orders of magnitude. I wonder whether power-factor penalties were originally determined as representing the actual cost of a lower power-factor, or whether they were designed to act as a deterrent. If the former then the need for applying capitalization results is even more pronounced than for losses.

I should like to endorse Mr. Marshall's remarks on the quality of steel and to suggest that in Section 6 of the second paper the author has an irrefutable argument. If we take his figures and leave out the power-factor penalty, then the capitalized value of a 10% reduction in iron loss is £27 per ton of steel. Since the iron, using the author's pre-war figures, was £30 a ton, it means that it is worth while paying nearly double for the iron to get a 10% improvement in losses. Irons have been available at a much less cost than that giving a 10% improvement, but they have been used to only a very limited extent. This again raises the question why these capitalization values, when they are appreciated and recognized, are not applied directly in practice.

Mr. Leslie Smith: Designers of apparatus have for the last fifteen years fully appreciated the economic soundness of lower losses, and the author is therefore preaching to the converted. As a body, designers have been willing to reduce losses provided they know how far they have to reduce them, and this, of course, depends on many factors, such as cost of energy, room available, etc. The author seems to have ignored the question of size and weight of plant, which might bring in its train very heavy extra capital costs.

In Section 1.3 of the first paper the author refers to two bases of choice of electrical plant, "output choice" and "economic choice," and says "the former consists in assembling at the lowest manufacturing cost the lowest quantity and *quality* of active materials. . . ." I do not think that he can mean that, because it is the experience of most designers that to get the lowest first cost it is more frequently necessary to use the *highest* quality of materials even where the importance of losses is ignored.

In recommending that an efficiency value be specified there is a further point that the author ignores. Most designers are very familiar with the situation which arises when an inordinate reduction of loss is required; it is possible in these circumstances so to pile active material into a design that the first cost soars, and in an effort to obtain an unreasonably high efficiency the increase in first cost may be greater than the capitalized value of the annual saving in losses. The best way to deal with the situation is for the purchaser to make known his operating costs and conditions, and the rate of interest he is paying on capital expenditure to obtain the apparatus and provide its housing, and then for the designer, with the technique that he can apply, to reach the optimum solution to the common benefit. It is rather difficult to set out these data, but it might be possible to set forth in a document under the auspices of the British Standards Institution the fundamentals in general form which would enable purchasers to substitute their own particular values.

Dr. E. Billig: The author has shown there is something amiss with transformers under the economic conditions obtaining in the last ten years or so. Put briefly, the cost of iron losses and magnetizing consumption is too high. There is no doubt that under the conditions assumed, the capitalized overall cost of the two transformers cited as examples in Table 2 could be considerably reduced by lowering the flux density. Mathematically, it is quite easy to find the density giving a minimum overall cost. The author has only partly solved that problem as he merely

gives an indication whether, in any particular case, the density should be raised or lowered. The two increments in cost in Table 2 constitute, mathematically, the components of the total increment in cost, which would have to be put equal to zero to obtain the "optimum" flux density. (The ratio of these two increments introduced by the author and called "economic disadvantage" is rather unnecessary and irrelevant in a mathematical sense.) In the cases cited, that optimum density comes to 10 520 gauss for the 15-MVA and to 9 050 gauss for the 2·5-MVA transformer. Repeating the calculations for a 10-year life, the results are not greatly different.

In spite of the results of such calculations, practical engineers are disinclined to build transformers with these very low densities. If transformers can be built technically with flux densities of 14 000 and, by the use of special core construction, as high as 16 000 or 17 000 gauss, every endeavour should be made to use these high densities. Other means should be sought to offset any disadvantage resulting from these densities, namely, either power-factor correction or further improvements in sheet steel.

Power-Factor Correction: Capacitors of a size required for the compensation of the magnetizing consumption of large transformers are obtainable at a cost of about 25s. per kVAr (pre-war prices are given throughout to be comparable with the author's figures) with an economic life estimated at about 10 years. The losses in such a capacitor—about 0·2% of its rating—are negligible. Over the same period, the power-factor penalties incurred for each kVAr would amount to £5 5s. The difference of £4 per kVAr represents the net saving accruing from the installation of capacitors. In Table 2, the main item against "overrunning" is the power-factor penalty. If power-factor correction is used, that item is considerably reduced. Repeating the calculations cited above, but using the cost of the capacitor instead of magnetizing consumption, the optimum flux density comes to about 13 000 gauss. In other words, this transformer as originally designed already represents the most economical solution.

Improvements in Sheet Steel: Higher-quality steels have been available for some years, though at a comparatively high cost. It can easily be shown that to obtain an economic advantage with these sheets, the increase x in cost must be less than the decrease y in losses, multiplied by a factor $N \cdot p_w/p_0$, where p_0 is the first cost of sheets in £/ton, p_w is the cost of the iron losses in £/kW, capitalized over the lifetime of the transformer, and N is the iron loss in kW/ton at the density at which the transformer is actually operated. For the 15-MVA transformer cited, with $p_0 = 30$ £/ton, $p_w = 122$ £/kW, and $N = 2{\cdot}25$ kW/ton, the increase in cost x must be less than 9·15 times the decrease in losses. A 10% decrease in the losses should thus be worth while, even if the steel is 90% more expensive. An improvement in magnetic properties is usually associated with any reduction of iron losses. The incidental reduction in magnetizing consumption can then be utilized by pushing flux densities more towards the existing technical limits. This would result in a general reduction of the main dimensions and weights, and thus represent real technical progress.

In conclusion, some authoritative body should undertake and clearly state the results of such an investigation. It should draw the attention of all types of consumers to it, who might then be prepared to pay a somewhat higher price for their machinery, which would prove an investment in the long run.

Mr. R. V. M. Shinnie: With reference to induction motors, the iron loss in terms of W/lb can be reduced by using a different grade of steel. Against that, however, the B/H curves for steel with a lower loss per lb invariably indicate a higher magnetizing current, and this would give rise to an increase in the copper loss of the machine. It would have been of interest if the author had further analysed the ratio of copper loss to iron loss, in order to show the resultant effect on these losses of selecting two or three different grades of steel having successively lower iron losses but increasing copper losses.

Mr. R. H. Coates (*communicated*): The papers are of value to those endeavouring to achieve "economic efficiency," but the methods given are not sufficiently practical for the paper to constitute a reference for calculations of this nature. The author does not stress sufficiently that the comparison of the initial first cost of the higher-efficiency equipment, which is a known real extra cost, has to be weighed against a probable hypothetical extra cost of probable hypothetical losses over a probable extensive period. Once this is fully realized, it is seen that it is not the present tariff of the supply which must be applied to the losses but the probable average tariff over the period considered, and when considering a period of 20 years it is immediately obvious that large errors are possible. For instance, who ten years ago would have imagined that the price of coal would have doubled by 1943? A further uncertainty of the future is the permanence of the assumed duty on the equipment. Because a machine is run for 27·4% of the time, it does not necessarily mean that in six years' time it will not be run at 6·8% or possibly 100% of the time.

These are the major uncertainties, and very naturally they make a responsible engineer reluctant to accept somewhat complicated mathematical calculations at their face value. The alternative the author gives in Section 1.10 of years of operation to recover the extra capital charges has a great advantage, for it gives clearly the length of time on which the estimate is based, and I think the facts the practical engineer requires to know are: (1) how long it will take to get his money back, and (2) the probable range in this time, due to errors of calculation.

The supply undertaking with which I am associated has for many years bought transformers to a specification that includes an efficiency clause in which the total annual charges are given as £$(0{\cdot}08C + 1{\cdot}85Lc + 9{\cdot}8Li)$, where C is the capital cost of the transformer in pounds, Lc the copper loss in kW at full load, and Li the iron loss in kW. The basis of the formula is not widely dissimilar to that used by the author, but the figures are pre-war and need considerable adjustment for present conditions.

Tenders for transformers have resulted in alternative designs being submitted with different efficiencies and, speaking generally, the extra cost of the high-efficiency equipment would be recouped for the smaller transformers in 13–16 years, and for the larger transformers in 5 years. It is interesting to note that, for other reasons, the flux density has been limited by the specification to a maximum of 11 500 gauss, and no alternative high-efficiency design has ever been submitted for a flux density lower than this. The author's conclusion in his second paper indicates that this density figure is close to that giving the greatest economy.

Mr. H. M. Lacey (*communicated*): The author bases his arguments and calculations on the assumed permanence of the electricity supply tariff and of the rate of interest on borrowed capital. The first can be determined scientifically and should not vary much with time, though it may be subject to geographical variation; the second cannot be controlled by the engineer and may be subject to wide variation. The best economic design is thus subject to arbitrary variations and it would be necessary to determine an acceptable basis of calculation if the author's recommendations were adopted. Very large transformers might be designed to suit any special circumstances, but this would hardly be practicable for motors or for transformers of small and medium sizes.

Referring to the second paper, the effect of the magnetizing component of the no-load kVA is dependent on the power factor of the load, being negligible at unity power factor and reaching a maximum at a power factor equal to that at no-load, i.e. of the order of 0·15. If the tariff and the load power-factor are such that the cost of the magnetizing current is appreciable, then the

proper solution would seem to be to install capacitors or other means for improving the power factor as a whole, rather than to deal only with the magnetizing component.

In his first paper, the author comments on the effect of war on his general arguments: Even in peace time it is desirable that the more general issues should be considered. From the national point of view, it may be necessary to consider such questions as whether the power is derived from coal or water, whether the materials under consideration are home produced or imported, and whether these materials can be regarded as limited or unlimited in quantity.

The author's arguments deserve very serious consideration. Even though the general principle may be sound, it does not follow that it will be easy to secure acceptance of that principle. My own experience of designing for maximum overall economy is that the design with the lowest first cost is almost invariably selected by the purchaser. I strongly support the author's conclusion that collective action should be taken to remedy the present state of affairs.

Mr. L. W. Law (*communicated*): I should like to support the author's conclusions that an improvement of iron quality by even a relatively small amount justifies a very considerable increase in what can be paid for the iron. Transformer sheet available immediately before the war, varied from a guaranteed loss of 0·63 W/lb to 0·49 W/lb at 10 000 gauss, 50 c/s, in 4 grades. Yet the better grades were not used to the extent that might be expected, had the principles in the author's paper been applied.

Mr. E. Mills (*communicated*): The author, by focusing attention on the relative importance of the first cost of plant and the cost of working losses, has done a good service to both users and manufacturers. Where motors are used in small works supplied on a kW tariff, it appears that for *average* use, such as Duties 3 and 4, the most economical flux and current densities are already being used in standard machines.

In large factories supplied on a tariff where the fixed charge is based on kVA demand, most of the savings suggested in the paper can usually be effected by installing a capacitor to improve the power factor of the whole installation. One advantage of this method of improving power factor over that of installing motors working at low flux densities is that, if some of the motors have to be changed after a very short life, owing to the machines into which they are built becoming obsolete, the capital sunk in the capacitor is not lost, as it would be if it had been spent on large-frame motors.

It has been suggested that there must be something very wrong with a tariff which enabled a consumer to save such large sums on his power bill by simply improving the power factor of his machines. When it is remembered that every ampere of lagging current demands an increase of carrying capacity throughout a vast supply network from the station alternators to the consumer's service, it is clear that any useless current which can be saved represents a large saving in capital charges for the supply authority, and this can be returned to the consumer in the form of reduced charges.

With transformers used for distribution and continuously on circuit, there is a good case for using low flux densities or, preferably, the highest quality of steel obtainable. This applies particularly in distribution where the maximum life is exceeded from plant. As this type of transformer usually runs at about 50% full load for all but a few weeks in the year, a small increase in copper losses, if accompanied by lower iron losses, would normally be economically sound.

Mr. R. B. Rowson (*communicated*): I can confirm the great value of the equation $P=kH^n$ for checking prices and for making estimates of prices from incomplete data. From the practical point of view, the figures are of course plotted on double logarithmic paper.

To-day with taxation at a very high figure, it is very difficult to decide on what basis one should capitalize annual savings to compare them with increased first costs. It would be useful if the author could give further consideration to this aspect of the matter in his reply.

One great difficulty in arriving at the optimum value of iron losses is the contrary effect their reduction has on the copper losses. Though the equations in the paper point unmistakably to the advantage of reducing losses they cannot be used for arriving at a decision. Before the recent Statutory Order, quotations would normally be obtained for a transformer with standard losses and for one with the same copper loss and, say, 10% lower iron losses. As a rule the alternative proves to be the more economical proposition. The makers are then naturally asked for a unit with still lower losses, the price for which proves to be much higher owing to the increased length of copper conditioned by the larger iron circuit. If some general expression for this factor could be worked out it would be of great help in deciding the proportions for the most economical transformer.

[The author's reply to this discussion will be found on page 217.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 29TH NOVEMBER, 1943

Mr. R. S. Orchard: In Section 2.13 of the first paper the author refers to the effect of flux density on system operation. I am not convinced that the increase in transformer noise, or difficulties due to harmonics except where very lightly-loaded lines are concerned, or difficulties of parallel running, are likely to arise in practice where the general system design is sound.

I agree with the action recommended in Section 2.15 that each particular job should be considered on its own merits, but I think the author paints too black a picture of the cost of transformer losses and that the figures given in Table 2 of the second paper should not be allowed unduly to influence the choice between a high or a low flux density for transformers.

The author has compared two transformers, one over-run and the other under-run. Neither of these conditions is normal or economically the best available. For purposes of comparison, therefore, I have taken at random two pairs of transformers and compared their losses with those the author has selected. The figures given are comparable with those in Table 2 in that the constants used are those given by the author in Table 1 of the second paper. Each pair of transformers was designed for similar working conditions, one with a lower and the other with a higher flux density. The losses quoted are those actually obtained during test after manufacture. The prices are related to present-day levels since in this way the best picture of the current situation is obtained. I have also shown the saving both for the above transformers and for those in Table 2 assuming the magnetization losses not chargeable.

It will be seen that, in place of the considerable economic disadvantages of 12·4 and 5·1 shown by Item 21 in Table 2, figures of 1·03 and 2·5 might be obtained in practice. It appears, therefore, that even if magnetization losses are chargeable it is quite possible that a higher-flux-density transformer is worthy of consideration in each case.

If the magnetizing losses are not chargeable it seems there is a considerable economic advantage in the use of a higher flux density, and I should like to have the author's views on this point.

It would also be interesting to know what percentage of consumers, in his view, do pay for their magnetizing consumption,

Table A—Comparison Calculations

			66 kV	33 kV
Transformer C (higher flux density).				
1	Rated output	MVA	15	7·5
2	First cost	£	9 870	5 370
3	Copper loss at full load	kW	119	56·7
4	Iron loss	kW	31·0	16·5
5	Magnetizing consumption	kVAr	293	119
6	B_{max} in core and yoke	kilogauss	13·5/12·5	13·8/11·8
7	B_{max} effective mean value (assumed)	kilogauss	13	12·8
Transformer D (lower flux density).				
8	Rated output	MVA	15	7·5
9	First cost	£	10 500	5 720
10	Copper loss at full load	kW	110·8	65·8
11	Iron loss	kW	36·5	11·82
12	Magnetizing consumption	kVAr	189	47·5
13	B_{max} in core and yoke	kilogauss	11·6/10·4	11·5/10
14	B_{max} effective mean value (assumed)	kilogauss	11	10·75
Cost differences between higher and lower flux densities.				
16	Iron loss (Line 4 − Line 11) × 122	£	− 560	+ 242
17	Magnetizing loss (Line 5 − Line 12) × 8·85	£	+ 920	+ 640
18	Copper loss (Line 3 − Line 10) × 35·3	£	+ 290	− 322
19	Total losses cost excess (Line 16 + Line 17 + Line 18)	£	650	889
20	First cost saving (Line 9 − Line 2)	£	630	350
21	Economic disadvantage of higher flux density (Line 19 ÷ Line 20)		1·03	2·5
22	Total saving by use of higher flux density if magnetization loss is not chargeable			
	(*a*) *A* − *B*	£	230	20
	(*b*) *C* − *D*	£	900	101

since I understand that the cost of energy to a large number of consumers is unaffected by the power factor of the load.

Dr. R. Willheim: I should like to comment on the author's conclusions regarding the economic flux density in large supply transformers in the light of foreign developments. He considers economic disadvantage as being inherent in current practice, but the examples given in Table 2 reveal that this new judgment is based on his method of capitalizing the magnetizing consumption. Capitalizing formulae used on the Continent and in the U.S.A. assess the full-load copper losses at £12–40 per kW, and two to four times as much for iron losses. There are, however, good reasons for not including a kilovar term. The assessment of the cost of reactive power is rather arbitrary as no general agreement has resulted. The chargeable fraction of the investment tends to drop to one fourth by the greatly increasing introduction of capacitors for the supply of local kilovar requirements. Besides, is it consistent to neglect entirely the reactive consumption caused by the leakage flux which at full load is about five times the magnetizing consumption? Why should transformers be penalized for consuming kilovars during light-load periods, when in large cable systems and h.v. overhead transmission systems shunt reactors are installed for the very same purpose? Moreover, in our systems we have twice the capacity of large transformers provided by small distribution transformers, with about four times the total magnetizing consumption.

During the last decade core-steels of 14 mils thickness have been steadily improved. The old guarantee of 1·48 watts/lb at 15 000 gauss, representative of Continental specifications, is obsolete. Present-day losses guaranteed for 15 000 gauss are about those previously valid for 14 000 gauss, or even 13 400 gauss; in the latter case the cost of the sheets is about 25% higher, entailing an increase of about 2·5% in total first cost. American and Swedish pre-war qualities are better still.

When German designers were faced with the problem of loading gauge, the flux density had to be raised, particularly with completely-assembled truck-mounting stations up to 100 MVA. It was not thought that large transient currents might develop on energizing, as modern types of Continental circuit-breakers make in air, thus switching near the voltage crest value. The problem of higher harmonics, certainly much overrated, was solved by the introduction of core designs with smooth sinusoidal magnetizing currents, proposed by Biermanns and myself; their application amounted to 2 000 000 kVA with unit sizes from 3 to 100 MVA.

The author directs our attention to modern magnetic materials combining lower losses and lower magnetizing consumption, though in the direction of the grain only. Cold-rolled steel does not require more than 10 ampere-turns/cm at 15 000 gauss, which holds good at present for 13 000 gauss. The increase in cost of 30% raises the total first cost of the transformer by about 3%. Some new design features will be involved, but there is every indication that a substantial increase in the flux density of large transformers is imminent.

Mr. T. F. Catliff: While the technique suggested undoubtedly provides users with an approximate yardstick for measuring their tenders for plant, I think the author will agree that the maker is in the best position to co-ordinate performance and maximum economy with other limitations in design. It is to be regretted that the author has gained a wrong impression regarding the attitude of transformer manufacturers, at any rate to this question. Transformer makers do not need a change of heart, as they are already fully alive to the desirability of manufacturing transformers with performances giving maximum economy in the service for which they are required. They are keen to co-operate with and advise users in this matter, but are helpless without data, or where the results of the capitalization of running costs are regarded as "paper figures" of doubtful value.

In this country the user very rarely specifies complete data for the capitalization of losses, and I suggest the author would have been more correct if he had styled users' specifications without this information as lamentably incomplete. In trying to educate users in this direction, it is not uncommon to tender three or four alternatives, when with complete data a single offer could be made. More and more export buyers are including complete data in their inquiries and regularly purchasing low-loss plant.

I agree that much remains to be done to ensure that transformers are designed for a maximum economy on a capitalized basis, and that there are few cases where the economic iron loss will not be appreciably below the losses of a minimum-cost design.

Whether this is obtained by improved material or reduced flux density can be left to the maker, the main thing is that the correct economic iron loss should be offered. In practice, I find the same condition applies to the economic copper loss, which seems to disagree with the author's conclusions. Here I find conditions generally justify a reduction of the minimum-cost design loss by 12–18% for average conditions and up to 22% for heavy-duty conditions, representing costs for reduced losses of £20–60 per kW reduction in loss.

I agree with the author's findings in the second paper. Here again makers have been pressing for improved material, with reduced losses in mind, rather than considering the practicability of increasing flux densities. It is to be hoped that the price of the low-loss plate referred to will not be double that of pre-war grades, or British makers will be faced with as heavy a handicap as ever in the export market.

Mr. W. L. Kidd: The author has unfortunately had to base his calculations of the effects of variation in flux density on transformer costs on prices ruling in 1934. Considerable changes have taken place since then and I have, therefore, worked out the 33-kV example in Table 2 using current prices. The index n and the constant K differ appreciably from the author's figures, with the result that the economic disadvantage of over-running the 33-kV transformer iron becomes 1·7 as against his figure of 5·1. These figures assume that the magnetizing consumption is to be capitalized, but as previous speakers have mentioned it seems difficult to justify this procedure; especially with bulk-supply transformers. For example, on an extensive 66-kV cable system in the London area capacitance current is very troublesome during periods of light loading, and there could be little justification in charging the cost of magnetizing current against the bulk-supply transformers on this system since the magnetizing current actually improves the system conditions.

It seems reasonable to hope that careful design and the use of a suitable quality of iron will enable manufacturers to keep magnetizing current for transformers working at flux densities of the order of 13·5 kilogauss, to values very little, if at all, in excess of the magnetizing current for 11·5-kilogauss transformers, and at the same time to maintain the same efficiency and ratio of copper to iron losses. This has been almost achieved in some transformers recently purchased, but here the magnetizing current was increased about 50 per cent; nevertheless, an appreciable reduction in first cost and weight was obtained.

It has been evident for some time that manufacturers in America have had the advantage of a new type of sheet steel, and it is to be hoped that soon after hostilities cease manufacturers in this country will get improved steels. Dr. Brailsford* in his paper on electrical sheet steels has indicated the possibilities both as regards low loss and high saturation point.

So far as I am aware, the transformers installed since 1938 and operating at 13·5 kilogauss, have not given rise to any harmonic troubles, although they were made with the sheet steels in general use by the industry at the beginning of the war and did not incorporate the special winding arrangements outlined by a previous speaker.

Returning to the question of magnetizing current, I have found that tender estimates of magnetizing current and the actual measured values differ considerably; usually the tender figure is 50–100 per cent in excess of the realized figure. B.S. 171 states that "no load current is not considered to be a subject for guarantee and therefore, no tolerance is given." Since the author suggests that magnetizing kVA should be capitalized, is he in favour of including magnetizing current among the guarantee figures and assigning to it a tolerance in line with those of Table 7 of B.S. 171?

The author does well to draw attention in Section 2.15 of the first paper to the unreasonable use of forced cooling on motors, which always results in reduced efficiency and higher losses. I suggest that many purchasers of motors pay little attention to efficiency and losses, because in many factories electricity charges form a comparatively small proportion of the total production charges. In one factory I was told this was less than 1 per cent.

Mr. C. Turnbull: Regarding Kelvin's method for calculating maximum all-round efficiency including financial charges, I have long advocated the term "least loss" or "minimum loss," which I think preferable to the American "dollar efficiency." An increase in efficiency from 95% to 96% does not seem much, but if one says that the losses have been reduced from 5% to 4%, a 20% reduction, it gives more encouragement for effort in this direction.

Some 30 years ago I suggested the use of powdered iron for transformer cores. It was proposed to fill the powder into containers with separators to reduce eddy currents and to compact it under magnetic influence to cause the particles to set themselves along the lines of force. I understand this method is now used for telephone transformers; I still think it worth looking into for large transformers.

Amenities must be considered as well as efficiency. Some transformers are noisy. I have known an old transformer with slack laminations which made as much noise as a blacksmith's shop; it was near a noisy factory and people had become accustomed to it and did not complain. Noise in a residential district may, however, be objectionable.

Mr. W. T. Maccall: I think some of the speakers have rather missed the point of the papers. It is not a question whether, by using better material, we can improve transformers, but whether, with any given material, the present design is the best in all respects when the cost of the losses is also included. That seems to be the essence of the papers, and we should be grateful to the author for propounding a method whereby any particular case can be analysed, although not necessarily taking his figures.

For motors, which are rather more complicated but in some ways as important, he gives a rule equating the cost to a constant × (power)^n. Three years ago I went into the cost of induction motors, and the figures I had would fit in with a rule of that sort, but only over a comparatively short range. It seems to me that, taking the 6-pole slip-ring motors for which he gives 0·71 for n, my figures would be 0·62 for small sizes (up to 20 h.p.), rising, according to the size, up to 0·72 at 100 h.p. I would like to know how closely any particular figure would cover as big a range as he says. Would it not be more accurate to alter the index as the size of the machine alters? For small motors the rate of increase of cost with size is different from that for the larger motors.

There is another minor point on which I am not quite clear. In Section 2.11 of the first paper, the author gives the effect of changing voltage, and he assumes that the flux density varies with the voltage and gets a shunt copper loss varying as the voltage raised to a power of 1·6–1·9. But if the flux density is increased by a given percentage the shunt current must be increased by roughly three times that figure, while the shunt-loss percentage increase should be six times as large and not twice as large. He gives "2 —" as the power; this seems to me to be wrong. It would be correct if the field rheostat were unaltered, but the other indices for the voltage would then be reduced, since the flux would be only $\frac{2}{3}$ of 1% more.

[The author's reply to this discussion will be found on page 217].

* "A Survey of Electrical Sheet Steels for Power Plant and the Factors affecting their Magnetic Properties," *Journal I.E.E.*, 1943, 90, Part II, p. 307.

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 6TH DECEMBER, 1943

Dr. W. Wilson: The author has forged what may justly be termed the "missing link" in the chain of designing, specifying, and selecting motors and transformers by substituting direct calculation for guesswork. His method will check the pedantic insistence on the use of needlessly expensive designs, as well as remove the temptation to sacrifice reliability and endurance for the sake of cheapness.

I endorse his conclusion on the excessive flux density of transformers, though for a reason he has not included in Section 7 of the second paper. The adoption of over-run designs led about 10 or 15 years ago to a considerable increase in the transient switching current, which seriously complicated the application of balanced protective gear since the current enters and does not leave the transformer and thus behaves exactly as a fault. It may be for this reason that separate protective schemes are now commonly installed on the primary and secondary sides, instead of a single sensitive scheme.

Regarding the selection of the correct size of motor for a given function, especially in the many cases when the load is variable or intermittent, I suggest the necessity for a more scientific rating than the "rule of thumb" method employed in Clause 72 of B.S. 168. For this purpose a performance curve is required of each rating of motor which connects the load with the time required to reach a specified temperature. I have shown* how such a curve can be readily compiled, or its equation calculated, if the machine time-constant be known. The latter quantity, which incidentally affords a true measure of the "size" of the machine, should be laid down in the specification in place of the crude provision lumping motors into three groups, with only three time periods jumping from 2 hr to 30 min and then to 15 min. It is obvious that only the most approximate calculations can be made on the basis of information with steps of this coarseness, while actual figures are given vaguely and appear at best to be careful guesses.

Mr. W. P. Richardson: The basic problem raised by this paper is—how much iron and copper can we afford to lock up in electrical plant in order to economize coal in the future? Whether we can arrive at a reliable solution by equating everything to currency, which varies in purchasing power with time and place, seems to me to be very doubtful. Broadly speaking, there have been three periods in the commercial development of our industry: First, a period of unrestricted competition; secondly, a period of agreement as to price, and one of competition as to performance, the general effect of which has been to improve both performance and quality; and thirdly, a movement to relate price to performance, and of this the papers seem to be a part.

In Section 2.15 of the first paper the author says "the motive power can only come from the purchaser, who must demand a higher-efficiency article and be willing to pay more for it." In over twenty years I have met only one such purchaser, so it would appear that the author is starting a new crusade. There are several cases, often misunderstood, where real economy does not depend on high efficiency, for example, squirrel-cage motors for frequent starting duty such as for operating lifts, cranes, and hoists, where most of the energy is used in acceleration, and consequently the inertia, or size, must be kept to a minimum. Other examples are machine-tool motors for operations requiring frequent reversal. Built-in types of motor, too, are often restricted as to size. To all these the paper does not apply, but on the other hand there are many cases of continuous-duty machines operating on a high load factor where high efficiency at increased cost will pay.

* "The Estimation of Overload Periods for Electrical Equipment," *World Power*, 1936, 25, p. 8.

The paper suggests a purchasing engineer wrestling with numerous alternatives between which the difference is small, and manufacturers working out these alternative quotations. Since only some 12 per cent of inquiries became orders, and in view of the need of standardization to effect economy in manufacture, it is to be hoped that if the ideas in the papers are generally adopted there will be some agreed simplification.

I disagree with the author on the question of fans. These are no longer a last-moment addition to reduce temperature rise, but are an integral part of the motor and type of enclosure. One cannot make a perfectly smooth rotor with minimum windage; there must be some arrangement to produce movement of air to get rid of heat caused by losses, and of the few alternative ways of doing this a fan of considered design is at least as economical as any other.

Dr. R. G. Jakeman: I am particularly interested in the way the author has harnessed mathematics to this problem. Further explanation on a few points appears desirable. In the first paper, I think that the figures for the 10-h.p. size in Table 7 should be inserted in Table 8. In the first column of Table 8, the values for d.c. motors do not seem quite consistent; starting at 1 500 r.p.m., the value goes up for 1 000 r.p.m., down for 750 r.p.m., and up again for 500 r.p.m. Is there some explanation for this?

It would be an advantage to have a little more explanation as to how to use the tables. Taking Table 8, we know that the 10-h.p. motor on a certain duty has an economic advantage ratio, i.e. it will be economical to under-run that motor. How do we know the right size of motor to take? Must the answer be got by trial and error calculations?

In Table 6, it appears most remarkable that a curve of the form $P = kH^n$ is applicable to such a variety of quantities. Is there some physical significance in this, or is it entirely empirical? I have checked some of the curves for the top line in the Table and I agree with the constant and the index for the copper loss. For the magnetizing loss I agree with the index, but I think that the constant is too low. I suggest that the figures in the paper only refer to the magnetizing current at no-load; they should evidently refer to the total wattless current on load, which would make a considerable difference. With regard to the price curve, I have only checked that one line but I cannot make it agree; it appears that a straight line would be much nearer to the actual figures, so that the formula would become $P = kH + n$. How would this affect the calculations of the result of 1% change?

Mr. E. Tobin: Transformer and machine designers do indeed consider economics; they have to do so in the choice of materials and design, and where capitalization formulae are available they can design for the lowest total cost.

I cannot agree with some of the author's remarks, for example his condemnation of fans. On a 30-MVA transformer, open to world competition and designed for lowest total cost (the capitalization data being available), we obtained the lowest capitalized value by using a fan to assist the cooling above half load, even though the highest grade of steel was used and the flux and current densities were very low to reduce the losses.

There would be a greater advance in transformer development if flux density could be made higher by using an improved grade of steel with low loss and high permeability. The only benefit obtained by working at low flux densities is the lower working point on the B/H curve and lower iron losses; nothing is gained from the reserve capacity of the iron as the supply voltage cannot be altered, whereas working at low copper densities can give a reserve capacity for overloading. If the steel makers can help by providing a steel having low loss and a good B/H curve, and which can be worked at high flux densities, we can design trans-

formers with low copper losses and good regulation, thus effecting other savings such as less loss on load tap-changing equipment. The electrical industry is comparatively young, and supply companies have been built up gradually; therefore costs are not sufficiently stabilized to risk additional money in transformers and machines in the early stages. The load factor changes, events like the war affect supply conditions, and many of the factors ruling are difficult to predetermine.

For hydro-electric plant we use the highest possible densities because power is cheap, and plant cost is reduced to a minimum. One hydro-supply company leaves the street lights of a mountain village burning all day and night as it is cheaper than installing switches.

Haulage costs and foundations are a problem for transformers rated at over 60 MVA, and low flux densities will limit the maximum size that can be built.

Mr. W. S. Burge: The author has developed an elaborate relationship between technical design and economic theory, but has overlooked the fact that his whole structure stands on a very unstable foundation. To relate technical design to economic theory, it is necessary to capitalize the design features through their period of useful life, and also to relate the cost of such features to reasonably accurate load factors throughout the life of the apparatus. In addition to this, a reasonably accurate estimate must be made of the tariffs or cost of electricity throughout the useful life of the apparatus, and also a reliable forecast of the cost of competitive sources of power such as coal, gas or water. The majority of motors and transformers are built for a useful life of some 20 years, but very few, if any, purchasers have the remotest idea of how these variables may drift during such a period.

If the author were in the position of a purchaser, how would he apply his economic considerations in the absence of any reliable knowledge of the use to which his apparatus would be put during its life? I think he would follow the practice of most other users, in purchasing the nearest standard product for supplying his requirements for the immediate future of the first two or three years in the life of the apparatus and let later years look after themselves.

Viewing the subject broadly, it appears to me that a concerted effort to follow the advice given in this paper would seriously conflict with the requirements of standardization in design. I consider the need for standardization to be far more important than the problem of making scientific design fit more accurately to the detailed duty of the apparatus. The author will agree that our common objective in all matters of design and manufacture is to give maximum value for money, and this I suggest can be better achieved by standardization than by design based upon fine discrimination to satisfy a sub-division of duties.

Mr. G. S. Buckingham: I think the author has omitted from his calculations several points which must be taken into account by engineers purchasing new plant. It is not possible to assume an unlimited supply of capital. A buyer may have to choose between spending additional money on a high-efficiency motor or on a new machine tool for his business, and might decide that a better return for his money was offered by investing it in his own business. Or a supply engineer may buy a large transformer and spend extra money to have a low iron loss and low magnetization consumption only to find that he has reduced the reactance of his transformer and thus increased his short-circuit output, in fact to such an extent that he has to spend more money on external reactors or on switchgear with a higher rupturing capacity.

I think the author has attached too much importance to the power-factor penalty due to magnetization consumption. It is not unreasonable to suggest that about half the motors or transformers in service in factories are not subject to power-factor penalties. The C.E.B., of course, do not pay Grid tariff for their supplies, and supply engineers can often balance the cost of the power-factor penalty by taking into consideration the capacitance of high-voltage underground cables.

The author's calculations are based on so many variables that his conclusions can only be accepted as pointers. It would require, in my opinion, a hypothetical economic disadvantage of at least 4 to 1, under all working conditions, before a designer could assume that his standard equipment required modification. Purchasers would have to judge in the light of all the circumstances whether additional capital should be expended in order to save future costs for losses.

Mr. D. P. Sayers: My principal reaction to this paper is a feeling that it is not quite fair to supply engineers, the general implication being that supply engineers have never heard of Kelvin's Law. All specifications for transformers that I have dealt with during the last six years or so have invariably included a formula to bring into economic consideration both the iron and copper losses. Possibly these formulae may not have been as correct academically as the author would like, but they have proved a good rough and ready means of taking into account the economic effects of all losses. I think that the original Grid transformer specifications included an item in which iron losses were capitalized at £45 per kW. Apparently the subject was not entirely overlooked even some twelve years or more ago.

Caution is needed when designing where there are so many very wide variables. For instance, Tables 3 and 4 of the first paper show that the cheap, medium and dear supply prices vary by 4 : 1, and for the duty cycles the maxima and minima are in a proportion of 14 : 1. That variation of duties may apply quite well within a single undertaking. There is a very great risk in using any particular set of conditions as a justification for departing from established designs. I think experience has shown on the whole that the present designs (I refer to pre-war conditions) are substantially sound. The inclusion of loss formulae in transformer specifications gave manufacturers an opportunity of submitting alternative offers having different loss values. When these offers were compared on a true economic basis, namely that of total annual charges, the curve of these charges against losses was usually very flat. In other words, the standard offer was not far removed from the economic optimum, and there was little justification for departing from the standard and paying a higher price for a more efficient transformer.

Mr. R. H. Rawll: When we in Birmingham were engaged some years ago on the change in frequency from 25 to 50 c/s, it was, of course, necessary to reduce the inconvenience to the consumer to a minimum, and one method of doing this with regard to new motors was to install those of the dual-frequency type. Certain manufacturers made plant of this type, while others did not. The latter, when pressing their wares, emphasized that the dual-frequency motor was slightly less efficient; but while this, of course, was true, the interesting point was that the consumer installing these motors was not unduly worried about 1 or 2% difference in efficiency; his main concern was the reliability and life of the plant. It is important, therefore, to consider these factors as well and not merely the economies realized purely from the point of view of design.

There has been a large increase since the war in the use of built-in motors on individual tools and machines; this practice in its turn has naturally reduced the horse-power of the average motor in industry. These facts may invalidate the conclusions at which the author has arrived, since they raise a different economic problem, in that as the motor is supplied with the machine the cost and performance of the motor are in all probability unknown to the purchaser. What are the author's views on this matter?

Mr. T. Pickles: It is time a few words were said on behalf of the industrial engineer, who has been neglected, while quite a lot has been heard from the manufacturer's point of view. I think

the author has done us a service in developing this method of economic comparison. It is clear that in many cases considerable economies can be effected, but much co-operation will be required in the future between the industrial engineer and the manufacturer. Also there seems to be much scope for co-operation in influencing machine-tool makers who seem very unwilling to spend money on electrical equipment.

If the author's method is to be applied, as it ought to be in most cases where motors are being purchased, much staff work will be necessary. Bearing in mind the large numbers of small firms which do not yet have anyone higher than the grade of foreman on their electrical staffs, it is clear that there must be a very great influx of industrial electrical engineers in the future.

Mr. H. Hooper: If motor manufacturers paid attention to the various range of diversities mentioned in the paper, would it not be the very antithesis of any attempt at standardization? Also would this not affect mass production with its price advantages, especially as regards relatively small motors?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. D. J. Bolton (*in reply*): I shall first reply to general points.

Cost of Magnetizing Consumption. Messrs. Marshall, Norris, Kidd and Buckingham, and Drs. Billig and Willheim, question whether so much, or even whether any, charge should be made for reactive consumption. For motors and works transformers the deciding factor is not what is the real cost of this, but what does the plant purchaser have to pay for it. On this point, and in reply to Mr. Orchard, something like half the two-part industrial tariffs base their standing charge on kVA. There is also the much smaller Grid tariff penalty which is all that has been assumed for the transformer calculations. If the result of including a kVA charge is to produce an inordinately high economic-advantage ratio this may be, as Sir Frank Gill suggests, a criticism of the tariff, but it does not invalidate the economic decision on the data presented. In some cases, as Dr. Billig, Mr. Lacey, Mr. Mills and Dr. Willheim point out, the price assumed should be brought down to something approaching the cost per kilovar of condensers, but to this must be added the cost of housing the extra plant, the switchgear and switching operations necessary, etc.

Regarding distribution transformers, one can only say that many supply undertakings seem to be under the impression that lagging consumption costs them something or why do they charge their clients for it? Dr. Willheim voices the views of several speakers when he asks why transformers should be penalized for consuming kilovars during light-load periods when shunt reactors may be installed for the very same purpose. I might point out that my kilovar charge is in every case attached to the standing charge and so incurred when the transformer is on full load. It has to cover the costs incurred through the adverse effects on regulation, and also the effects of leakage flux referred to by Dr. Willheim. But this is not entirely a satisfactory answer if the self-same apparatus and kilovars are performing useful functions at other load periods. Ultimately, it is for the supply engineers to make up their minds what they want. If magnetizing consumption is, on balance, a liability and not an asset, they are right to charge for it in their tariffs, and I am right to allow for it in my calculations.

Life, Capital and Interest Rates. In reply to Messrs. Hoseason and Buckingham, my life estimate of 18–20 years was an attempt to cover the whole range from small motors to large transformers in a single set of figures; but multiplying factors are given down to an $8\frac{1}{3}$–10 year life, and these can be used for the smaller plant and the more uncertain situations. Other points mentioned, such as higher insurance, rent and rates, can all be covered by a small addition to the effective interest rate. Again, if capital is scarce and the load is charged at profit-making rates rather than at the rate appropriate to debentures, this will increase the interest figure but decrease the depreciation charge: the effect will not usually be greater than the "dear capital" assumption (nearly 8% overall).

Changes and Estimates. With regard to the subjects raised by Messrs. Coates and Burge, it has been pointed out that many plant purchasers regard future uncertainty as a "safety first" argument for choosing minimum first-cost and eschewing long-term views. I suggest that changes may take place in either direction, and that one cannot in any case avoid decisions based on future estimates. All one can do is to base them on the best estimates available, and not put in the least-price article when this has every probability of wasting more than it saves. A load factor, if properly selected, is as likely to go up as down, and a life, if intelligently estimated, is as likely to be exceeded as to be shorter. By all means let us make conservative estimates, but having made them let us have the courage of our calculations and put in the right engineering answer—the plant likely to be the cheapest overall. In the period quoted by Mr. Charley, copper and steel prices have increased by 27% and 60%, but the price of coal into power stations has increased by several hundreds per cent. The use of more copper and steel to save electricity, if made on the basis of my pre-war figures, should now prove an even better bargain than it appeared at the time.

Mr. Coates makes a useful suggestion for appealing to the industrialist, namely that the saving can be expressed in the form of the years of recovery (of the capital) with a plus and minus figure to indicate the probable margin of error.

Price and Losses Curves. In reply to Messrs. Kidd and Maccall, and Dr. Jakeman, the assumption made as to the shape of the curves plotting price and losses to a base of rated output, is that for small changes the points lie on a straight line not passing through the origin. The purely empirical formula assumed is $P = kH^n$, where n is normally less than unity. The curve could equally well have been represented by $P = k_1 + k_2H$ for such small portions of its length, and the choice is purely one of convenience. Moreover, widely different values of the constants, e.g. higher k and lower n, may reproduce approximately the same small piece of line and give almost the same results in the rate of change. For accurate results, the same constants over widely different sizes should clearly not be used.

Past Practice regarding Loss Capitalization. In reply to various comments by Messrs. Hoseason, Norris, Smith, Catliff and Sayers, I freely acknowledge the pioneering work of Mr. Hoseason and others in the crusade for higher efficiencies. Nowhere do I suggest that capitalization of losses has been omitted in the past, but merely that it has been insufficiently practised, frequently neglecting copper losses and usually neglecting magnetizing consumption, and that such features as the diversity on the standing charge and the load factor of the losses have commonly been overlooked or misunderstood.

Qualitative Improvements: Non-Standardization. In reply to Messrs. Catliff, Burge and Hooper, I would point out that my plan of basing all calculations on a hypothesis of larger standard machines is a device to overcome uncertainties of non-standard pricing, and by no means represents the best possible case or the most appropriate action. It does however avoid any departure from present manufacturing standards. If the results of this calculation indicate a strong case for action on economic grounds it is for the designer to determine what form that action should take, and to make the choice between the particular ideal and the economy of general manufacture.

Transformer Size and Weight Limitations: Transport. In reply to points raised by Messrs. Smith, Kidd and Tobin, I would point out that transformers made larger on economic grounds will not

necessarily occupy more substation space, since the tank and heat-dissipating gear may be smaller. Transport difficulties remain, but must it be assumed that whilst transformer designers march ahead, transport engineers stand still?

Supplementary Replies to Individual Contributors.

Mr. Marshall's reference to the pre-war adoption of 11 kilogauss for the Grid transformers indicates a remarkable proximity to the optimum economic values given in the papers. The high density values he quotes for German practice suggest to me technical but not economic "progress."

In reply to Sir Frank Gill, the terms "price," "plant cost," etc., have been used somewhat indiscriminately, but the figure intended is that portion of the total installation cost that is liable to vary with the choice in question. Frequently this will be merely the price from the maker. Regarding Section 2.1, I think that the compounding period will not affect the amounts paid in loan interest, but only those paid in depreciation provision.

Mr. Charley supports my concluding paragraphs that there is probably an even better case for economic selection in small transformers than in larger ones. The danger of over-running the iron through tap changing, to a point never intended by the designer, seems to be a very real one.

In speaking of the "lowest quality of active materials" I should perhaps have said grade. I had in mind different grades, say of insulating material in motor slots, all of good quality but some permitting better space factors and therefore less copper loss. I agree with Mr. Leslie Smith that the designer can produce the best results, only provided he has the full data.

In reply to Mr. Shinnie, if there is a danger of lower-loss steel having higher magnetizing consumption, this seems a further reason for including kilovar costs.

I am not convinced that the taxation rate affects the choice between higher first cost and higher losses cost. The difficulty Mr. Rowson mentions of a seesaw between copper and iron losses when using quantitative efficiency improvement is a very real one, which does not arise in qualitative changes, such as better steel. I know of no general expression, but only the method I employed of considering in turn small changes in the iron and copper separately.

Mr. Orchard suggests that neither over- nor under-running is normal or economically the best available procedure. I do not claim the device as being any more than a convenient yardstick, to use Mr. Catliff's phrase. The designer should certainly know best, though it may be that owing to the extra cost of non-standard manufacture my suggestion may actually prove the most economic. This is supported by Mr. Orchard's own figures. It is difficult to compare these point by point with my own, except to say that my price and loss curves indicate that, on the average, it should be possible to purchase a greater loss reduction for less cost than his figures indicate. This is particularly so in the 66-kV example, where the lower flux density must on the average mean less, not greater, iron loss.

Mr. Catliff testifies to the economic awareness of foreign buyers and helps to answer the objection often urged against higher-priced higher-efficiency plant that it cannot compete in export markets.

Mr. Kidd has re-worked my examples, using present-day transformer prices but the same tariffs as before. Since tariffs must ultimately reflect cost of plant plus cost of fuel, and since the latter has risen enormously, I cannot see the logic of this calculation. It assumes an entirely one-sided rise, and though there may be a lag in tariff increases this is hardly a stable basis for a recalculation. It is surprising to learn of actual values of magnetizing currents so much below the tendered figure. At full load—the condition under which the kVA charge operates—this is, however, likely to be more than balanced by the effect of leakage reactance mentioned by Dr. Willheim. I certainly think that magnetizing current should be included in the specification so long as a single kVA tariff or power-factor penalty is in force. In factories whose electricity charges form only 1 per cent of their production costs, the electric plant charges must be an even smaller proportion. The case for aiming at the best balance between the two is unaffected by their absolute magnitudes.

Mr. Turnbull's suggestion of minimum loss in place of maximum efficiency is only one step in the right direction. The different losses must be taken separately because they have different cost values, and the term "dollar efficiency" is perhaps an attempt to include this.

Mr. Maccall rightly draws attention to the main question which the paper attempts to answer, namely, with given materials, prices, etc., are the proportions of our expenditure on plant and energy the best possible? I must also thank him for a correction which has now been made in the paper.

Dr. Willheim seems to suggest that, because small transformers are the worst offenders, this is a reason for neglecting magnetizing consumption in the larger sizes. I do not for a moment doubt the capacity of Continental or British transformer designers to overcome any and every technical difficulty with which they are confronted. My only fear is that their consummate technical achievements may be mistaken for engineering progress. Real progress is not to squeeze greater output from smaller material but to get better service for less money.

Dr. Wilson has usefully added to my list of imponderables which favour under-running.

To Mr. Richardson and Mr. Tobin I should make it clear that I am not attacking fans as such, but merely the current attitude to fans, which seems to be that if these make possible a greater output without excessive temperature rise they are *ipso facto* a good thing.

Dr. Jakeman is expecting too much from the economic ratio figure. The precise magnitude is liable to be erratic and is not significant. The utmost one has a right to infer from it is that, if the value is between, say, $\frac{3}{4}$ and $1\frac{1}{2}$, the present rating is tolerably economic. If it is greatly below or above this range, over- or under-running, or corresponding design changes, are called for. As regards magnetizing current I have, as he said, used the no-load value. Since the power-factor penalty is incurred at full load when the wattless current is greater, it would seem that the cost I have calculated for magnetizing consumption is far from being the overstatement that other speakers have claimed.

Mr. Tobin and others make too much of my somewhat irrelevant addendum on steel quality. We all agree that better-quality steel is in every way desirable. The question under discussion is, with any given quality, etc., are we making the best use of our materials?

Mr. Burge and Mr. Hooper put the case for plant standardization and I have tried to comply with this in the assumptions I make.

Mr. Buckingham's last paragraph I would generally accept—and commend to Dr. Jakeman's attention—though 4 to 1 is a little unkind. I suggest that a ratio of 3 to 1 or over would justify a modification of design.

Mr. Sayers concedes the principle, but disagrees as to the amount. Admitting the wide range of the variables I think my figures show that, for the *average* situation, present designs are not on the whole the most economic.

In reply to Mr. Rawll, the advent of the individual drive and the built-in motor has meant a larger number of smaller motors. I do not think that size *per se* greatly affects the economic situation, but, if it means more intermittent use, then that will weaken the case for economic choice.

THE PROBLEM OF CONDUCTOR SAGGING ON OVERHEAD TRANSMISSION LINES*

By C. O. BOYSE, Member,† and N. G. SIMPSON, Associate Member.†

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SUMMARY

The paper consists of two parts. The first is devoted to a comprehensive review of overhead-conductor sags and tensions and their calculation on single spans and on complete lines, using parabolic formulae throughout. A standard procedure and standard methods of calculation are recommended.

The second part of the paper deals with the determination, from the point of view of the conditions prevailing in Great Britain, of wind and ice loads to be applied to conductors for design purposes and the stresses so produced in the conductors. The use of the term "factor of safety" when applied to overhead conductors is criticized, and suggestions are offered for revisions to the Overhead Line Regulations of the Electricity Commissioners. The loads transmitted to the supports are also considered. Erection sags for low-voltage distribution lines are recommended for general adoption.

(1) INTRODUCTION

The purpose of overhead lines is to transmit electric power, and the electrical properties and characteristics of the conductors are therefore of first importance. The designer's second consideration is to examine the mechanical properties of the conductors. These will determine the structural character of the whole line, influencing such factors as conductor spacing, span length, and the height, shape and strength of supports.

Conductor sags and tensions are governed in Great Britain by the Electricity Commissioners' Overhead Line Regulations, which define the minimum loads and maximum stresses to be allowed for. The making of the actual calculations involves either the solution of cubic equations giving approximate results, or the use of hyperbolic functions giving exact results. It is therefore not surprising that, even after many years of experience, there is a lack of uniformity in the methods of calculation adopted by supply-undertaking engineers, consulting engineers and contractors.

The choice between the use of the parabola or the catenary as a basis of calculation is largely a matter of personal preference. Little importance can be attached to the relative degrees of accuracy achieved by the two methods, as even in extreme cases the use of parabolic formulae gives results which are satisfactory in every way.

In any case, it must be remembered that extreme accuracy in the making of sag calculations is of no practical value when consideration is given to the effect of: (*a*) The arbitrary nature of the maximum wind and ice loads adopted in the design. (*b*) Inaccuracies in the making and plotting of profile surveys. (*c*) The indeterminate effect of the longitudinal flexibility of supports on the sags in individual spans of a complete line. (*d*) Variations in the elastic properties of the conductors from those assumed in the calculations. (*e*) The difficulty of assessing correct erection temperatures. (*f*) Inaccuracies in the adjustment of erection sags in the field.

In this paper parabolic formulae are used throughout, with a description of the procedure to be adopted if greater accuracy is necessary in special cases. The formulae given are not new, but they are indispensable to the paper. They are expressed in a concise form which, if adopted as a standard, would greatly facilitate the exchange of ideas on sagging problems.

The second part of the paper, dealing with the framing of regulations, is self-explanatory, and the objects of the paper may be stated as follows: (i) To encourage the use of a standard notation and procedure, and of standard methods of calculation. (ii) To recommend, from a study of the theoretical and practical considerations involved, revisions to those clauses of the Electricity Commissioners' Overhead Line Regulations dealing with conductor sagging and the loads imposed by the conductors on the supports.

(2) GENERAL PRINCIPLES

(2.1) Single Spans

(2.1.1) **Definitions.**

The principal terms used throughout the paper are defined as follows:

Span.—The span length is the horizontal distance between two adjacent supports.

Sag.—The term "sag" is used to denote the distance, measured in the direction of the resultant load on the conductor, between the conductor and the mid-point of the straight line joining the two supports. This definition also applies to non-level spans, and the numerical value of the sag in such cases is, on the basis of the parabola, exactly the same as for a similar level span with the same horizontal tension. The sag as so defined is also the maximum distance, measured in the direction of the resultant load on the conductor, between any point on the line joining the two supports and the conductor.

Tangential Tension.—The direction of the actual tension at any given point in a conductor is along the tangent to the curve of the conductor at that point, and is thus referred to as the "tangential tension."

Tension.—Unless otherwise indicated, the word "tension" shall denote the horizontal component of the tension in a conductor, such horizontal tension being uniform throughout any one span.

(2.1.2) **Fundamental Formulae.**

The following equations are all based on the parabola, and assume that the load per foot of span is equal to the load per foot of conductor.

List of Symbols.

S = sag, ft.
S_v = vertical component of sag, ft.
l = span length, ft.
T = horizontal tension under load w, lb.
T_T = tangential tension, lb.
w = load per foot of conductor, lb (including weight of conductor).
w_v = vertical component of w, lb.
A = actual cross-section of conductor, in^2.
d = overall diameter of conductor, in.

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† Callender's Cable and Construction Co., Ltd.

E = modulus of elasticity of complete conductor.
α = coefficient of linear expansion of complete conductor per deg F.
t = temperature rise, deg F, from initial to final condition.
a = difference in level of adjacent supports, ft.
y = horizontal distance of lowest point of curve from lower support, measured towards higher support. (If the lowest point is outside the span y is negative.)

$$C_1 = \sqrt{\left(\frac{EA}{24}\right)};\quad C_2 = \alpha EA$$

Relation between Sag, Span, Load and Tension.

$$S = \frac{wl^2}{8T} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$S_v = \frac{w_v l^2}{8T} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

Relation between Sag (or Load and Tension), Span and Length of Conductor.

$$\text{Length of conductor} = \left(l + \frac{8S^2}{3l}\right) \quad . \quad . \quad . \quad . \quad (2)$$

$$\text{or} \qquad \left(l + \frac{w^2 l^3}{24T^2}\right) \quad . \quad . \quad . \quad . \quad (2a)$$

Relation between Tension, Load and Temperature for any given Span Length.

$$\left(\frac{C_1 w_2 l}{T_2}\right)^2 - T_2 = \left(\frac{C_1 w_1 l}{T_1}\right)^2 - T_1 + C_2 t \quad . \quad . \quad (3)$$

The suffixes 1 and 2 denote initial and final conditions respectively.

Sloping Spans.

$$y = \frac{l}{2} - \frac{aT}{w_v l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$\text{Vertical reaction at higher support} = w_v(l - y) \quad . \quad . \quad (4a)$$

$$\text{Vertical reaction at lower support} = w_v y \quad . \quad . \quad . \quad (4b)$$

Equations (1) to (3) enable all initial sag and tension calculations to be made, and, except in special cases involving very long spans or very steep slopes, give results which are more than accurate enough for all practical purposes.

During the setting-out of a line on the profile survey, it is usually necessary in hilly sections to consider cases of reduced or excessive weight loading on supports. Such cases may be examined by the application of equations (4), (4*a*) and (4*b*).

(2.1.3) **Closer Study.**

If, for any reason, e.g. in the case of very long spans or very steep slopes, it is necessary to determine the relation between sags and tensions to a high degree of accuracy, a more critical study of the problem must be made. Fig. 1 illustrates the general case of a suspended conductor and may represent any span.

As stated, the preceding formulae ignore the difference between the load per foot of span and the load per foot of conductor. A more accurate determination of the load per foot of span can be made by increasing the load per foot of conductor in the ratio of conductor length to span length. From Fig. 1 it is seen that the value of this ratio is

$$\frac{\sqrt{(l^2 + a^2)} + \frac{8S^2}{3l}}{l}$$

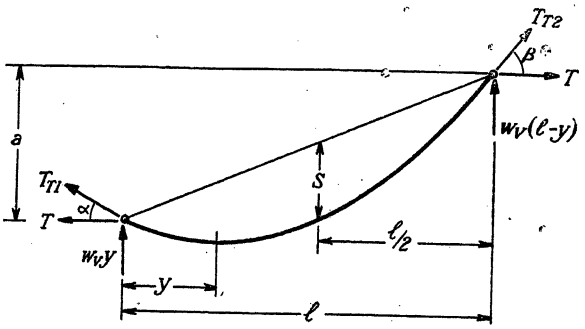


Fig. 1.—General case of suspended conductor.

Hence the corrected load per foot of span

$$= w\left\{\sqrt{\left[1 + \left(\frac{a}{l}\right)^2\right]} + \frac{8}{3}\left(\frac{S}{l}\right)^2\right\} \quad . \quad . \quad . \quad (5)$$

In normal cases it is assumed that the horizontal tension is the maximum tension that will occur in a span. In actual fact the maximum conductor tension will be the tangential tension at a support, and, referring to Fig. 1, the relation between T_{T2} and T is as follows:

$$T = T_{T2} \cos\left[\text{arc tan}\,\frac{(4S + a)}{l}\right] \quad . \quad . \quad . \quad (6)$$

Similarly

$$T = T_{T1} \cos\left[\text{arc tan}\,\frac{(4S - a)}{l}\right] \quad . \quad . \quad . \quad (6a)$$

On level spans, the relation between horizontal and tangential tensions may be more readily obtained from the expression

$$T = T_T - wS \quad . \quad . \quad . \quad . \quad . \quad (6b)$$

In equations (5) and (6) all the terms are known accurately except S, for which one or more approximations may be made, as necessary.

Accurate values for conductor load and horizontal tension having been determined, they may be substituted in equation (1) and the sag calculated in the ordinary way.

(2.1.4) **Loads on Supports.**

The calculation of the horizontal transverse loads transmitted from the conductors to a support is straightforward. Fig. 2

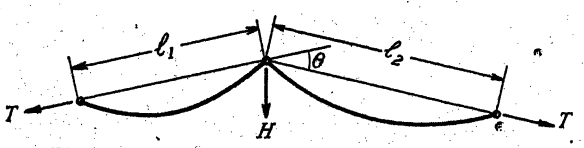


Fig. 2.—Horizontal transverse load on a support.

represents any two adjacent spans in plan, the conductors being deflected under wind.

It is reasonable to ignore the reduction in both the wind per foot of conductor and the horizontal tension T due to the fact that the wind cannot act normal to both spans at once. On this basis, the total horizontal transverse load is

$$H = 2T \sin\frac{\theta}{2} + \frac{w_h(l_1 + l_2)}{2} \quad . \quad . \quad . \quad . \quad (7)$$

where w_h is the wind per foot of conductor and T is the total horizontal tension under the resultant conductor load w. Equation (7) makes full and accurate allowance for the increase in the effective angle of deviation at the support due to wind.

The resultant conductor tensions in the new directions are made up of two components—first, the longitudinal conductor tension as normally calculated; and secondly, the actual transverse wind load causing the deflection. For a support at a straight-line position, when $\theta = 0$,

$$H = w_h(l_1 + l_2)/2$$

Reference has been made in Section 2.1.2 to the calculation of vertical reactions at supports. These are important to enable cases of excessive weight loading on elevated supports, and reduced weight loading or uplift on lowlying supports, to be detected. The actual values of the vertical reactions may be obtained from equations (4*a*) and (4*b*). The temperature and loading conditions giving the most severe results must be selected; these will invariably be at the minimum temperature, with wind, or with wind and ice.

Care must be taken, in using the equations (4), (4*a*) and (4*b*), to substitute the maximum horizontal tension T due to the resultant load w, and the vertical component w_v of the resultant load w.

(2.2) Complete Lines

(2.2.1) Factors Influencing Design.

It is necessary in connection with every transmission line to make investigations into the values of the conductor sags and tensions under the following four main headings: (*a*) Maximum sag (to ensure that the specified ground clearance is maintained). (*b*) Maximum tension (to ensure that the maximum permissible tension is not exceeded). (*c*) Conditions of minimum vertical sag (for the purpose of calculating abnormal vertical loads on elevated and lowlying supports). (*d*) Erection conditions (to enable the appropriate erection tensions and sags to be calculated).

(2.2.2) Behaviour of Spans of Different Lengths.

In making sag calculations it is first necessary to fix a basic condition of loading, temperature and tension from which tensions and sags at other conditions can be derived. This basic condition is usually that of maximum loading and minimum temperature when the conductor tension is limited to a specified maximum figure. The application of this basis to a range of spans necessarily results in the tensions at all other conditions varying with span length. Therefore, the resulting erection tensions in still air at various temperatures, and the minimum still-air tensions from which the maximum possible sags are derived, will be different for all span lengths.

(2.2.3) Lines on Rigid Supports.

If it is intended that the conductors on a line of perfectly rigid supports shall exactly develop their maximum permissible tension on all spans, it follows from the remarks in the previous paragraph that every length of span must be strung independently to its own particular erection tension. Even if this be done, the minimum tensions (corresponding to maximum still-air sag conditions) will be different on all span lengths, which will make it impossible to check the ground clearances on the profile by using a single maximum-sag template throughout. Alternatively, the minimum tension may be fixed as a constant for all spans, in which case a single maximum-sag template may be used, but the resulting maximum tensions will vary with span length.

In practice, however, conductors are invariably run out over rollers or pulley blocks, this procedure necessarily resulting in a constant erection tension throughout the conductor length. The effect on conductor tensions in individual spans at other loading and temperature conditions may be seen from a study of Fig. 3, in which the full lines represent typical span/tension curves based on the assumption that the maximum permissible tension will occur in all spans under maximum load, the resulting minimum-tension curve being used for determining the maximum still-air sags and the corresponding ground clearances.

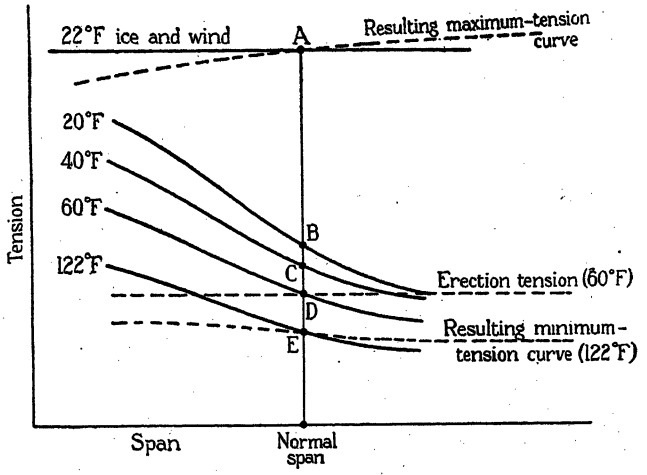


Fig. 3.—Tension chart for rigidly supported conductor.

For the purpose of illustration a span is selected as representing the "normal" span for a line, and points A, B, C, D and E therefore indicate appropriate tensions for that span. It is then assumed that a length of conductor is erected over a number of different spans at the tension D, thus giving the horizontal broken line through D. When load or temperature changes occur, all spans other than those of "normal" length will develop tensions different from those shown in full lines. All spans shorter than normal will have lower tensions than originally calculated, and spans longer will have tensions greater than originally calculated. The top and bottom broken-line curves show that the maximum tensions in the spans longer than normal will exceed the permissible limit, and the maximum still-air sags on spans shorter than normal will be greater than expected. This conclusion depends upon the slope of all the erection-tension curves being downward from left to right, as in Fig. 3, which is almost invariably the case.

If no tolerance is allowed in the specified maximum tension it is necessary to prohibit span lengths exceeding that for which the erection tensions have been calculated. In other words, the erection tensions must be calculated from the maximum span. If this procedure is adopted, the maximum sags for all shorter spans will be greater than expected (to an extent which itself varies with the divergence between the erection temperature and the temperature at maximum sag), but the corresponding minimum tensions will still vary with span length, and it is still impossible to check the ground clearances on the profile by using a single maximum-sag template throughout.

To summarize the case of a line on rigid supports, the need for constant erection tensions results in the maximum permissible tension being exactly developed on one span length and on no other. This span length will be referred to as the "basic span" and, as explained above, must be the longest span in the line. Similarly, the minimum tension, corresponding to maximum still-air sag conditions, will also inevitably vary with span length.

(2.2.4) Freely Supported Lines.

On a line on which the conductors are free to move longitudinally at the intermediate supports instead of being secured to them, it is impossible for any unbalanced longitudinal tensions to develop at such supports. Consequently, the tension throughout any particular section between rigid points will be constant

under any given conditions. The tension variations due to load or temperature changes will depend on the lengths of the spans in the section, and it is shown below that the section as a whole will react to load and temperature changes in the same way as a single span which will be referred to as the "equivalent span" of the section.

Let l_1, l_2, l_3, l_4, etc., represent a series of spans supported on rollers, the total length of the section being Σl. It is required to determine the equivalent span l_E of the section, which can therefore be regarded as consisting of n spans each l_E in length, i.e. $nl_E = \Sigma l$.

Consider the series of spans l_1, l_2, etc., under an original loading of w_1 lb/ft and a tension of T_1 lb, and allow the tension to change to T_2 lb under a load of w_2 lb/foot, with any given temperature change. Then the total length of conductor under the original conditions is given by

$$\Sigma l + \frac{w_1^2}{24T_1^2}\Sigma l^3$$

and, under the final conditions, by

$$\Sigma l + \frac{w_2^2}{24T_2^2}\Sigma l^3$$

That is, the change in total length is given by

$$\Sigma l^3\left(\frac{w_2^2}{24T_2^2} - \frac{w_1^2}{24T_1^2}\right)$$

Similarly the total change in the length of conductor in n spans each l_E long would be

$$nl_E^3\left(\frac{w_2^2}{24T_2^2} - \frac{w_1^2}{24T_1^2}\right)$$

Now as the external causes of both these changes in identical lengths of the same material are similar alterations in stress and temperature, these changes must be equal.

Hence $$\Sigma l^3 = nl_E^3$$

or $$\Sigma l^3 = \frac{\Sigma l}{l_E} \cdot l_E^3$$

from which $$l_E = \sqrt{\left(\frac{\Sigma l^3}{\Sigma l}\right)} \quad \ldots\ldots\ldots \quad (8)$$

This equivalent span length may be used as the basis for calculating the tensions under all conditions of loading and temperature, such tensions being, of course, constant throughout the section. In fact, each section of the line between rigid points can be treated for the purpose of calculation as a single span, and the whole line is therefore comparable with a series of separate spans on rigid supports. The only difference between the two cases is that whereas it is practicable to string each complete section of a freely supported line to its appropriate equivalent span erection tension, the individual spans on rigid supports cannot in practice be so strung.

This difference is of considerable importance as it enables the sagging of a freely supported line to be based on either a constant maximum tension throughout or a constant minimum tension throughout. In the first case, the minimum tension will vary with equivalent span, thus leading to the previously mentioned difficulty with maximum-sag templates. In the second case of constant minimum tension, a single maximum-sag template can be used for all sections, but the maximum tension will be exactly developed on one equivalent span length only, namely the "basic equivalent span," which may be taken as the maximum equivalent span.

(2.2.5) Summary of Procedure.

None of the various types of overhead-line construction can be said to correspond exactly to either of the two extreme cases just considered. Nevertheless, it is common practice to regard pin-insulator lines as rigid, and suspension-insulator lines as freely suspended, although there is a growing tendency, which the authors support, to regard the type of light support used on pin-insulator lines as flexible enough to justify the classification of such lines as freely supported. Whichever view is taken, it is desirable to define suitable working rules, and Table 1 gives the correct procedure.

Table 1

Rigid lines	Freely supported lines
1. Fix normal span	Fix normal span
2. Fix maximum span, this to become the basic span	Fix maximum equivalent span, this to become the basic equivalent span
3. Apply maximum permissible tension to basic span and calculate erection tensions (which apply to all spans) and minimum still-air tension (which applies to basic span only)	Apply maximum permissible tension to basic equivalent span and calculate minimum still-air tension (which applies to all spans throughout line)
4. From above erection tensions determine minimum still-air tensions for range of spans	From above minimum tension calculate erection tensions for range of equivalent spans

The procedure set out above for rigid lines is admittedly laborious and some simplification is justifiable when dealing with pin-insulator lines, which, in any case, are certainly not perfectly rigid. At present, calculations for pin-insulator lines are generally based on the normal span length, all tensions derived therefrom being applied to the whole range of spans. This satisfies the fundamental requirement that the erection tensions, at any rate, must be constant for all spans, and in effect corresponds to the application of the theory of flexible supports with a fixed and predetermined equivalent span. At the same time, the authors consider that it would be preferable to treat pin-insulator lines in exactly the same manner as described above for freely supported lines.

An example of a sag chart, assuming rigid supports, is shown in Fig. 8. Although this is a somewhat special case it serves to illustrate the essential features already described of rigidly supported lines, namely constant erection tensions on all spans, resulting in variable maximum and minimum tensions. The basis of this chart is a maximum still-air sag of 3 ft 6 in on a 180ft span, this basis applying to a number of different conductor sizes. Corresponding erection tensions for the various conductors on a 180ft span give almost exactly the same erection sags, which have therefore been extended on a constant-tension basis to apply to all spans. The curves of maximum sag and maximum tension given in Fig. 8 have been derived from those erection conditions giving the highest values.

In the case of freely supported lines, the procedure outlined calls for no special comment and coincides with the best modern practice. A suitable form of erection-sag chart is shown in Fig. 4. To obtain any desired erection sag, the erection tension at, say, 60° F is read at B for an equivalent span A, the corresponding sag for an actual span of, say, 400 ft being obtained by projecting from B to C and from C to D on the lower scale.

The question of the inelastic stretch of conductors cannot be ignored, although its importance is sometimes exaggerated. The practice of pre-stressing conductors to high tensions during erection is to be deprecated, principally on account of cost. It is preferable to adopt the alternative procedure of reducing the

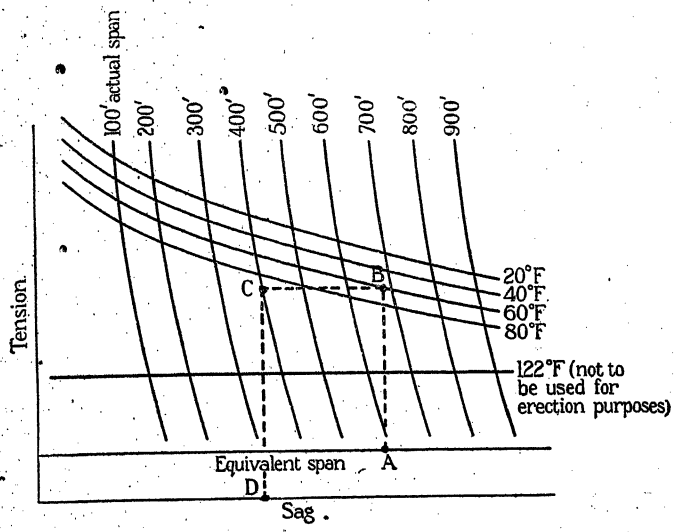


Fig. 4.—Erection sag and tension chart for freely supported conductors.

calculated erection sags by an amount up to, say, 10% according to circumstances. Little or no adjustment of the average medium-size line is usually required; adjustment is more necessary on long-span lines, particularly those provided with composite conductors.

(2.2.6) **Classification of Sag Templates.**

All sag templates are necessarily parabolic in shape, i.e. they satisfy the equation $y = ax^2$. Therefore, if two templates have the same height y for a given base x, they are alike in all respects. This fact enables a template to be identified by a single dimension, say the height in inches on a base of 5 in, and by giving each template an appropriate classification number a ready means is available for ascertaining whether any existing template made for one combination of sag, span and profile scales can be used for a new job.

The value of the classification number (C.N.) is taken as 1 000 times the height in inches of a template measured on a 5in base. The factor of 1 000 is introduced to ensure that a high degree of accuracy is obtained without using a decimal point.

For example, a template is required to suit the following case:

Sag on 400ft span = 10 ft
Vertical scale: 1 in = 20 ft
Horizontal scale: 1 in = 200 ft

The appropriate C.N. is given by

$$\frac{(\text{Sag on profile, in inches}) \times 5^2 \times 1\,000}{(\text{Span on profile, in inches})^2}$$

which, in the case under consideration, amounts to 3 125.

It is unlikely that an existing template with exactly the desired C.N. will be found, but this is immaterial so long as the percentage variation does not exceed the limits of experimental error in plotting.

It must be remembered that in choosing a maximum-sag template the C.N. selected should not be less than the calculated figure, as otherwise insufficient ground clearance may result. Similarly, in selecting a minimum-sag template the actual C.N. must not exceed the correct figure.

(3) REGULATIONS

(3.1) General

This section of the paper deals with the determination, from the point of view of the conditions prevailing in Great Britain, of wind and ice loads to be applied to conductors for design purposes and the stresses so produced in the conductors. The use of the term "factor of safety" when applied to overhead lines is criticized, and suggestions are offered for revisions to the Overhead Line Regulations of the Electricity Commissioners. The loads transmitted to the supports are also considered.

(3.2) Nature of Superimposed Loads on Conductors

Overhead lines have to be designed so as to resist mechanical loads which are derived almost entirely from the conductors. The direct effect of wind pressure on the supports is seldom of much importance and, except in the case of very high supports, it could safely be neglected. The nature and extent of the conductor loading are therefore of fundamental importance, in so far as such loading affects both the conductors themselves and the structures which support them.

It is not difficult to select from meteorological statistics a maximum wind velocity suitable for design purposes in any given territory. On the other hand, the formation of ice deposits on overhead conductors is a much more arbitrary matter, and when ice does occur it may on very rare occasions reach many inches in thickness. It is uneconomical, however, to require that lines shall suffer no damage when they are subjected to ice loading conditions which may arise only once in, say, 10 years, and which will probably not be even approached during the rest of the period. Consequently, it is logical to limit the first cost of construction by allowing for "reasonable" maximum conditions, even if occasional breakdowns do result.

Before proceeding with the determination of suitable design values for both external loads and internal stresses, it is necessary to consider certain aspects of safety margins on overhead lines.

(3.3) Factor of Safety

In the design of most engineering structures the values of the maximum external working loads are known accurately enough to make it unnecessary to take into consideration the possibility of collapse by overloading. For the reasons given above this does not apply to overhead transmission-line conductors and supports, failure of which on rare occasions of extreme wind and ice loading must be expected. To ensure consistency in design it is therefore important that overhead-line design procedure should take account primarily of the external loads necessary to increase the internal stresses to their extreme limits, with only secondary regard to the stresses produced at other conditions of loading and temperature. In other words, the method of fixing safe working stresses by dividing the ultimate stresses by a factor of safety is not appropriate to the case of overhead lines.

This conclusion may be confirmed by a study of the calculated external loads necessary to break conductors erected in accordance with the present Overhead Line Regulations.

It is a simple matter to derive from the basic formulae given in Section 2.1.2 the value of the load per unit length to be applied to a conductor to change its tension from one value to another, the temperature remaining constant. If w_1 and T_1 represent the load per unit length and the conductor tension respectively at the initial conditions, and w_2 and T_2 the final load and tension, then

$$w_2 = \sqrt{\left[\frac{(T_2 - T_1)}{C_1^2 l^2} T_2^2 + \frac{T_2^2 w_1^2}{T_1^2}\right]} \quad \ldots \quad (9)$$

This shows that, for a given conductor, $w_2/w_1 = T_2/T_1$ for infinitely long spans only, and that the shorter the span the greater the divergence from this linear relationship. To illustrate this point more clearly, Fig. 5 shows the variation in the calculated loads necessary to break various hard-drawn copper conductors

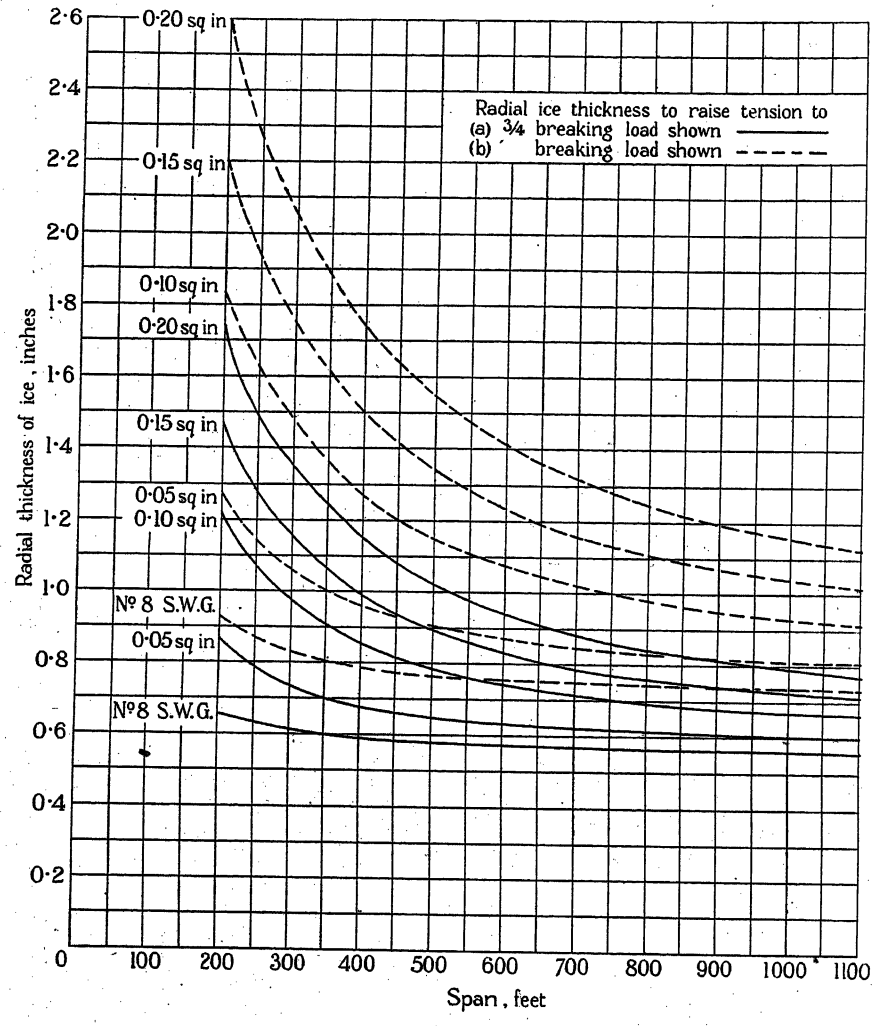


Fig. 5.—Copper conductors strung in accordance with Electricity Commissioners' Regulations for h.v. lines. Ice thicknesses which, with a wind load of 8 lb/ft², will stress conductors to three-quarters breaking-load and breaking-load respectively.

erected over a range of spans to such sags that they develop a tension of half breaking load when subjected to the loading prescribed in the Regulations of the Electricity Commissioners for high-voltage lines (a radial ice coating of $\frac{3}{8}$ in and a wind pressure of 8 lb/ft² on the ice-coated conductor). The loads are indicated by the ordinates to the curves, and are expressed as radial thicknesses of ice over which a wind pressure of 8 lb/ft² is assumed to act.

In addition to the ice thicknesses necessary to break the conductors, ice thicknesses are also plotted which will raise the conductor tension from half breaking to three-quarters of breaking strength. The resulting curves are all of the same general form, which is common to all conductors whatever their size or material.

The values shown have been calculated by applying the normal modulus of elasticity for each conductor over the whole range of stress. This procedure is not strictly correct, as the modulus of elasticity will decrease as the ultimate stress is approached. In actual fact, if allowance were made for the variation in the modulus of elasticity, the applied loads necessary to raise the conductor tensions would be increased. This increase would be greater on the short spans than on the long spans, and the curves would therefore slope even more steeply.

Fig. 5 shows clearly the fallacy of the common assumption that a fixed factor of safety implies a constant margin of strength, whatever the conductor material, size or span length. This weakness in the present method of fixing conductor sags and tensions has already been pointed out by A. Burke* and others.

The only true measure of the load-carrying capacity of a conductor is the amount of superimposed load necessary to increase its stress to the extreme limit, and in the authors' opinion the use of the term "factor of safety" in connection with overhead lines should cease.

It therefore follows that for design purposes it is desirable to specify a superimposed load to give the highest possible internal stresses in the conductors and supports. Such a load must still be an arbitrary one, and the possibility of its being exceeded must still be admitted. Nevertheless, it is possible, using past experience as a guide, so to specify the value of the superimposed load that the chances of its being exceeded are remote enough to make it uneconomical to allow for them.

In applying this principle to conductors, it might appear that the calculations should be made on the basis of the ultimate strength of a conductor, but this is open to the objections that a conductor cannot sustain a stress only a little below its ultimate strength without suffering damage, and that difficulties occur in the making of accurate calculations as it is impossible to fix a satisfactory value of the modulus of elasticity which can be applied throughout the whole range of stress from zero to ultimate. Consequently, the authors suggest that loads be specified to produce in the conductors three-quarters of their ultimate stress. Up to this limit, the conductors may be assumed capable of resisting indefinitely loading cycles corresponding to weather changes, and the use of the normal value of modulus of elasticity does not introduce serious errors into the calculations. Beyond 75% of the ultimate strength the conductors will almost certainly suffer permanent damage, and the 25% remaining cannot be regarded as capacity available for supporting still further load.

(3.4) Determination of Wind and Ice Loads

The present Overhead Line Regulations of the Electricity Commissioners specify a wind pressure of 8 lb/ft² on the projected area of ice-coated conductors, which corresponds to a wind velocity of 50 m.p.h. The chances of higher wind velocities than 50 m.p.h. occurring in this country are by no means negligible, but it is reasonable to assume that 50 m.p.h. is the highest velocity which will be experienced at the same time as the maximum allowable ice coating, the two effects together stressing the conductor to three-quarters of its breaking strength.

It is much more difficult to define the amount of ice loading to be allowed for, although it may be assumed that under any given weather conditions favourable to the formation of ice, the actual radial thickness of ice deposited will be the same for all

* "Some Problems in Transmission-Line Design," *Journal I.E.E.*, 1943, 90, Part II, p. 162.

conductors. On the other hand, economic considerations demand that lines of low electrical capacity shall withstand less severe weather conditions (and hence smaller ice thicknesses) than high-capacity lines. It may also be assumed, as a general guide, that the bigger the conductor the greater the importance of the line, and therefore the radial thickness of ice to be allowed for in the design should increase with conductor diameter. The problem, then, is to find a relation between conductor diameter and radial ice thickness which can be shown from past experience to be satisfactory.

With this object in view, Fig. 6 has been prepared showing, and cadmium-copper conductors, values are plotted assuming the tighter stringing resulting from the relaxed conditions now permitted by the Electricity Commissioners for light high-voltage lines. A point is also shown for 0·175-in² S.C.A. strung to present C.E.B. practice for 132-kV lines (27 ft maximum sag at 122° F on 900ft span). Physical properties of the selected conductors are given in Table 2.

The next step is to superimpose on Fig. 6 the curve of an equation connecting radial ice thickness with conductor diameter, which may be used for calculating the sagging basis of all conductors. It has already been stated that such an equation must

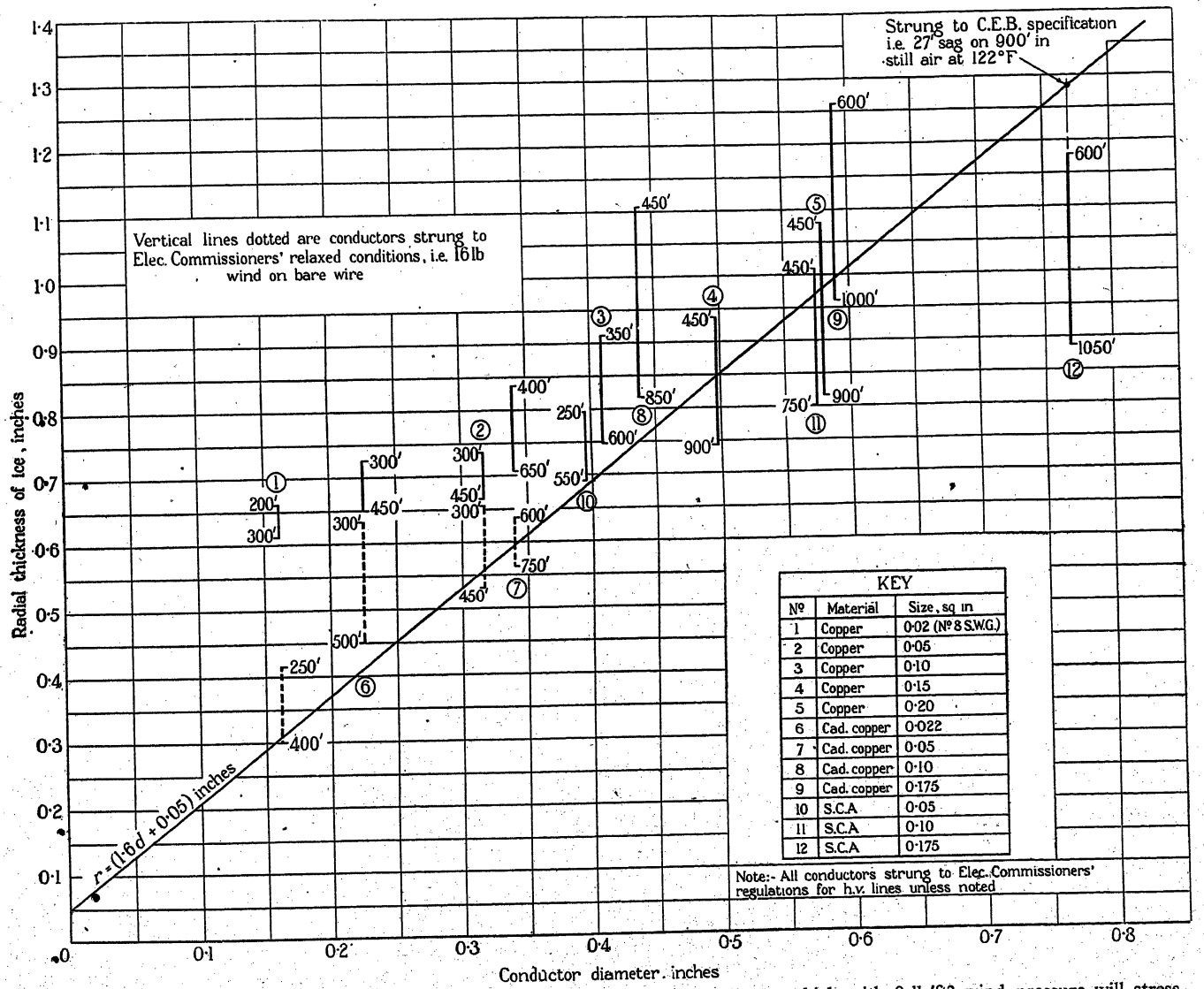


Fig. 6.—Various conductors strung in accordance with present practice: ice thickness which with 8 lb/ft² wind pressure will stress conductors to three-quarters breaking load.

in relation to conductor diameter, the radial thicknesses of ice which with a wind pressure of 8 lb/ft² will stress to three-quarters of breaking stress various conductors strung to present practice. The variation in load-carrying capacity with span length (already demonstrated by Fig. 5) is denoted by the plotting of a vertical line for each conductor covering its normal range of span lengths. All the conductors are assumed to have been strung in accordance with the Electricity Commissioners' Regulations for high-voltage lines. In addition, for the smaller copper be based on past experience. This experience leads to the following conclusions:

(*a*) Small conductors may safely be sagged to the relaxed conditions permitted by the Electricity Commissioners; that is, the tension at 22° F under a wind load of 16 lb/ft² on the bare conductor may reach 40% of the breaking strength. For example, the sag of a No. 8 S.W.G. copper conductor (0·16 in diameter solid) on a 400ft span may be considered satisfactory on this basis.

Table 2

PHYSICAL PROPERTIES OF CONDUCTORS

Material	Nom. area (equiv. copper)	Stranding	Diameter	Wt/ft	Breaking load	C_1	C_2
	in²		in	lb	lb		
Hard-drawn copper ..	0·02	No. 8 S.W.G.	0·16	0·079	1 266	124·4	3·42
	0·05	3/·147 in	0·317	0·200	2 915	195·4	8·45
	0·10	7/·136 in	0·408	0·399	5 873	276·2	16·88
	0·15	7/·166 in	0·498	0·594	8 527	337·1	25·14
	0·20	19/·116 in	0·58	0·789	11 550	388·2	33·34
Cadmium copper ..	0·022	3/·105 in	0·226	0·1016	2 227	139·6	4·31
	0·05	3/·158 in	0·34	0·230	4 667	210·1	9·76
	0·10	7/·146 in	0·438	0·459	9 467	296·6	19·45
	0·175	19/·118 in	0·590	0·819	17 083	394·9	34·49
S.C.A.	0·05	7/·132 in	0·396	0·144	4 105	223·2	12·79
	0·10	7/·173 in / 7/·076 in	0·574	0·304	9 270	324·0	26·39
	0·175	37/·11 in	0·77	0·570	17 720	441·6	47·74

(*b*) No appreciable change is necessary in the present sags of medium-sized conductors, e.g. 0·1-in² copper.

(*c*) Large conductors require a greater margin of strength (and hence larger sags) than the present regulations afford. The experience of the C.E.B. has shown that a 0·175-in² copper equivalent S.C.A. conductor should have a maximum still-air sag at 122° F of 27 ft on a 900ft span.

The straight line drawn in Fig. 6 through the two points corresponding to the typical cases (*a*) and (*c*) above is represented by the equation

$$r = 1{\cdot}6d + 0{\cdot}05 \quad . \quad . \quad . \quad . \quad (10)$$

where r = radial ice thickness (in) and d = conductor diameter (in).

The general effect of applying this law to the other selected conductors can now be seen. The new line cuts the individual conductor lines (or such lines produced where necessary) at points which correspond to the span lengths on which the new sagging basis is the same as the present.

It is also important to examine the maximum still-air sags which result from the application of the proposed formula. These sags, and the corresponding tensions, are shown in comparison with present practice in Fig. 7. The effect over the whole range of conductor sizes is governed by the conditions imposed by conclusions (*a*) and (*c*) above, and it may be seen from the maximum-sag curves that the desired results have been achieved in these cases without introducing appreciable changes in the sags on medium-size conductors. The authors therefore recommend that for overhead lines in Great Britain conductors shall be so strung that at 22° F their tension shall not exceed three-quarters of their breaking strengths when subjected to the following ultimate loads:

(*d*) An ice coating of radial thickness $(1{\cdot}6d + 0{\cdot}05)$ and

(*e*) A wind pressure of 8 lb/ft² on the ice-coated conductor.

Arising out of the previous reference to higher wind velocities than 50 m.p.h., it may be noted that the wind load in pounds per foot of conductor derived from the proposed formula for ice coating is $8(4{\cdot}2d + 0{\cdot}1)/12$. This is equivalent to $8(4{\cdot}2 + 0{\cdot}1/d)$ lb/ft² on the bare conductor, or at least 100 m.p.h. The corresponding resultant of this wind load and the weight of bare conductor is, of course, less than the resultant under conditions of ice and 8 lb/ft² wind pressure. Consequently, the stress in conductors strung to the design basis proposed and subjected to a 100-m.p.h. wind without ice loading will not reach three-quarters of their breaking strength.

The ice loading proposed is intended to be a minimum for Great Britain. This is consistent with the policy adopted by the Electricity Commissioners in framing their Overhead Line Regulations for securing the safety of the public. In those cases, however, where abnormal climatic or operational conditions are such that a greater reserve of strength is desirable on any particular line, the ice loading may be increased above that given by the formula. It is suggested that this result be obtained by increasing the term 0·05 to 0·25, or even 0·50.

The authors' proposals have been evolved after an examination of a number of other formulae, both linear and parabolic, all of which have been abandoned because the resulting sags on certain conductors differed greatly from the values which experience appears to show are safe. In many cases it is probable that experience is not yet conclusive, but the nature of the problem is such that it is not capable of complete solution on purely theoretical grounds. The proposals put forward by the authors are therefore based principally on practice, but with a background of what they consider to be sounder theory than now prevails. In some ways it may seem that the assumed radial ice thickness should not increase so rapidly with conductor diameter, in which case the actual formula proposed can be adjusted accordingly without departing from the essential principles outlined.

This problem does not appear to have been the subject of any previous comprehensive study on the basis adopted by the authors, although certain aspects of it are dealt with in the Memorandum dated May, 1930, by the British National Committee of the I.E.C. This Memorandum shows how one single formula may be adapted to the existing regulations in force in different countries on the assumption that the residual tension in an unloaded conductor is indicative of the reserve of strength necessary to enable the conductor to carry wind and ice loads. The present authors do not agree with this assumption and consider, as has already been stated, that the only true measure of a conductor's load-carrying capacity is the amount of superimposed load necessary to increase its stress to the extreme limit.

(3.5) Low-Voltage Lines

In order to limit the loads on angle and terminal supports it is desirable that the conductors on low-voltage distribution lines should be erected with much larger sags than the minimum permitted by either the present or the proposed regulations. This procedure, involving the provision of slightly higher supports, leads to a small extra cost which is more than offset by the saving at angle and terminal positions.

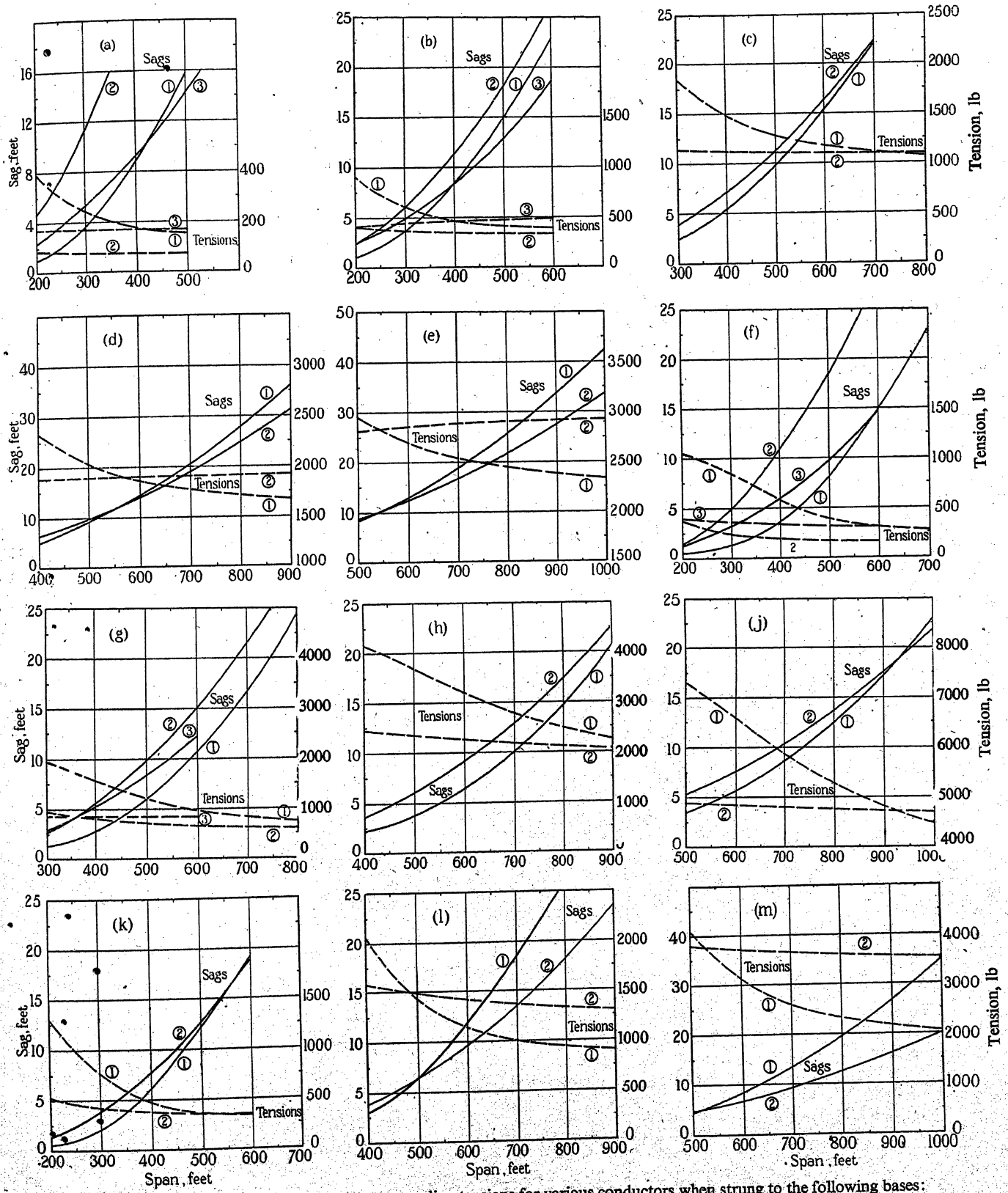


Fig. 7.—Maximum sags at 122° F in still air and corresponding tensions for various conductors when strung to the following bases:
(1) Ice thickness $(1{\cdot}6d + 0{\cdot}05)$ inches; wind load, 8 lb/ft²; temperature, 22° F; tension, 75 % breaking load.
(2) El.C. Regulations for h.v. lines; ice thickness, $\frac{3}{8}$ in; wind load, 8 lb/ft²; temperature, 22° F; tension, 50 % breaking load.
(3) El.C. relaxed conditions for h.v. lines; wind load, 16 lb/ft² on bare conductor; temperature, 22° F; tension, 40 % breaking load.

(*a*) No. 8 S.W.G. copper. (*b*) 0·05-in² copper. (*c*) 0·1-in² copper. (*d*) 0·15-in² copper. (*e*) 0·2-in² copper. (*f*) 0·022-in² cadmium copper.
(*g*) 0·05-in² cadmium copper. (*h*) 0·10-in² cadmium copper. (*j*) 0·175-in² cadmium copper. (*k*) 0·05-in² S.C.A. (*l*) 0·10-in² S.C.A. (*m*) 0·175-in² S.C.A.

Present common practice on low-voltage lines is to fix the maximum still-air sag on a given span at a constant value for all sizes of conductor. The authors recommend that this procedure should be continued, and that the stringing of all low-voltage lines should be based on a maximum still-air sag of 3 ft 6 in on a 180ft span. Fig. 8 shows how this value varies with span line. It is reasonable to assume that the maximum wind velocity that will ever occur on any line is 100 m.p.h., which represents approximately 32 lb/ft^2 on the projected area of conductor. Under these conditions, when the wind load in lb/ft on the bare conductors is $32d/12$, it is necessary to ensure that the supports shall not be stressed to the point of failure. This also applies

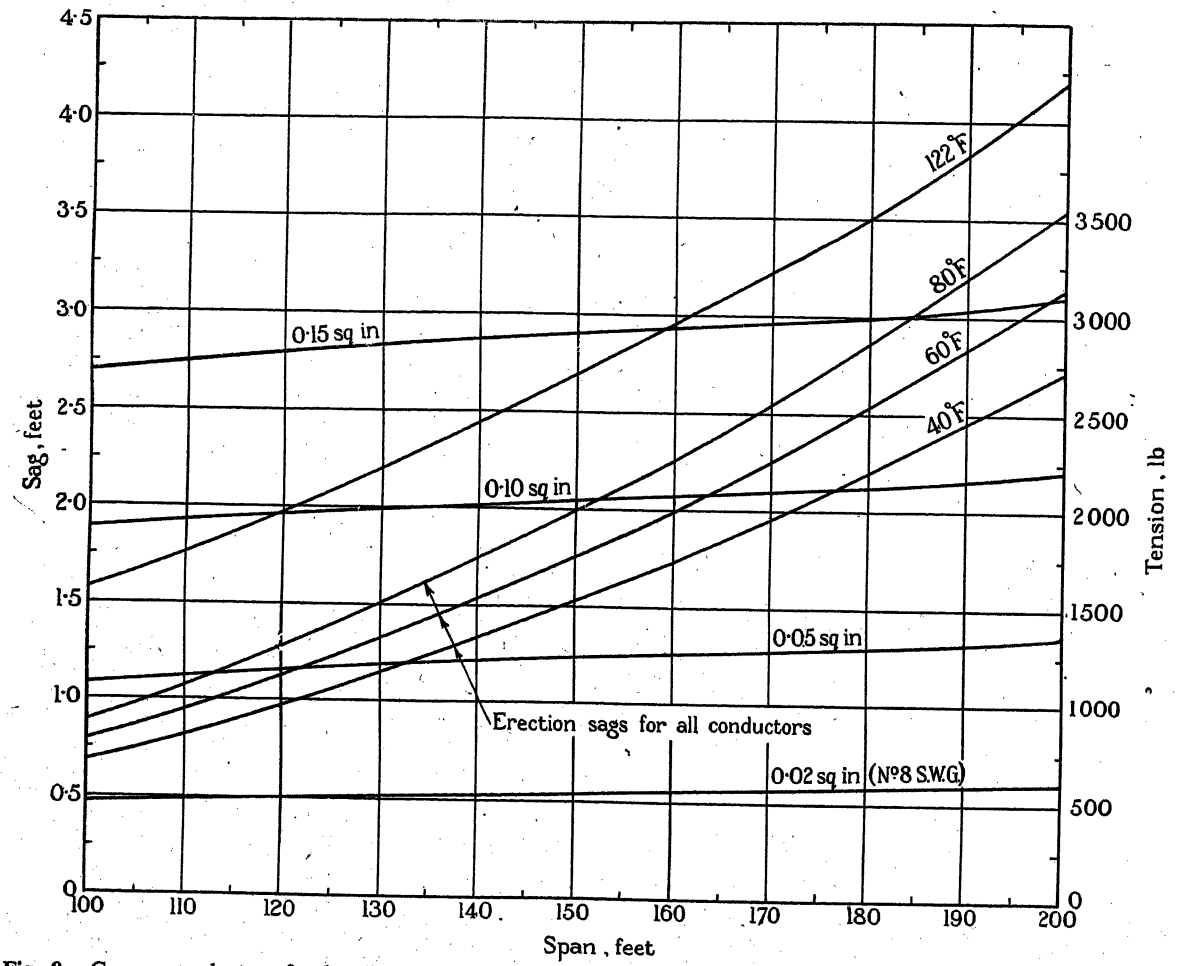


Fig. 8.—Copper conductors for l.v. lines strung to recommended basis: erection sags and conductor tensions under proposed ultimate wind and ice loading.

length and gives the corresponding erection sags at various temperatures. Fig. 8 also indicates the maximum tensions which will be developed in various sizes of copper conductors strung to these conditions and subjected to the ice and wind loading recommended by the authors.

(3.6) Loads Imposed on Supports

The authors propose that their recommendations for ice and wind loading should be used not only for determining conductor sags but also for calculating the loads which the conductors impose on the supports. This question is not strictly within the scope of the paper, but it must necessarily be taken into account in the framing of overhead line regulations.

Consider an overhead line with infinitely strong supports, the conductors being subjected to a gradually increasing wind load until they are on the point of failure. At this stage the conductors are carrying their maximum possible load per unit length—the resultant of the wind pressure on, and the weight of, the bare conductor—which in turn imposes on the supports the maximum possible overturning loads that can ever occur on that particular when the conductors are stressed to three-quarters of their breaking strength under the wind and ice loading given by the proposed formula, from which the wind on the conductors is $\frac{8(4{\cdot}2d + 0{\cdot}1)}{12}$ lb/ft. This value is greater than that given above as representing the maximum wind load which can ever occur on the bare conductor, and it must therefore form the basis of all calculations affecting the transverse wind load on supports.

Should it be necessary for any special reasons to reduce the conductor tensions on a particular line below the permissible values, it might appear that the supports should be designed to resist transverse loads greater than normal. This follows from the fact that the more loosely conductors are strung, the greater will be the value of the transverse wind loads which they can theoretically transmit to the supports before the conductors themselves are stressed to their limit. In practice, however, such a procedure would be considered extravagant, and it is more reasonable in such cases to ignore the possibility of any increase in conductor loading above the ultimate values given by the proposed formula.

The authors' recommendation is that those supports which are now required to have a factor of safety of $2\frac{1}{2}$ shall withstand without failure or permanent distortion the ultimate loads imposed upon them when the conductors are subjected to the proposed ultimate wind and ice conditions, such ultimate wind, deviation and terminal loads having first been multiplied by a "loading factor" of 4/3, thus ensuring a margin of strength in the supports as compared with the conductors. For wood poles, or any other types of support which are now required to have a factor of safety of $3\frac{1}{2}$, the "loading factor" should be $\frac{4}{3} \times \frac{3 \cdot 5}{2 \cdot 5}$, or say 2.

The present ultimate transverse wind loads together with the authors' proposals are given in Table 3.

Table 3

ULTIMATE WIND LOADS IMPOSED ON SUPPORTS BY CONDUCTORS

	Wind pressure (lb/ft²)	Radial ice (in)	Ult. wind load (lb/ft) on supports for which safety factor at present required to be—	
			2·5	3·5
1. El. C. Regs. for h.v. lines	8	$\frac{3}{8}$	$\frac{2 \cdot 5 \times 8(d + \frac{3}{4})}{12}$	$\frac{3 \cdot 5 \times 8(d + \frac{3}{4})}{12}$
2. C.E.B. Spec. for 132-kV lines	8	$\frac{1}{2}$	$\frac{2 \cdot 5 \times 8(d + 1)}{12}$	$\frac{3 \cdot 5 \times 8(d + 1)}{12}$
3. El. C. requirements for light h.v. lines ..	16	—	$\frac{2 \cdot 5 \times 16d}{12}$	$\frac{3 \cdot 5 \times 16d}{12}$
4. El. C. Regs. for l.v. lines	8	$\frac{1}{16}$	$\frac{2 \cdot 5 \times 8(d + \frac{3}{8})}{12}$	$\frac{3 \cdot 5 \times 8(d + \frac{3}{8})}{12}$
5. Recommended basis	8	$(1 \cdot 6d + 0 \cdot 05)$	$\frac{4}{3} \times \frac{8(4 \cdot 2d + 0 \cdot 1)}{12}$	$\frac{2 \cdot 0 \times 8(4 \cdot 2d + 0 \cdot 1)}{12}$

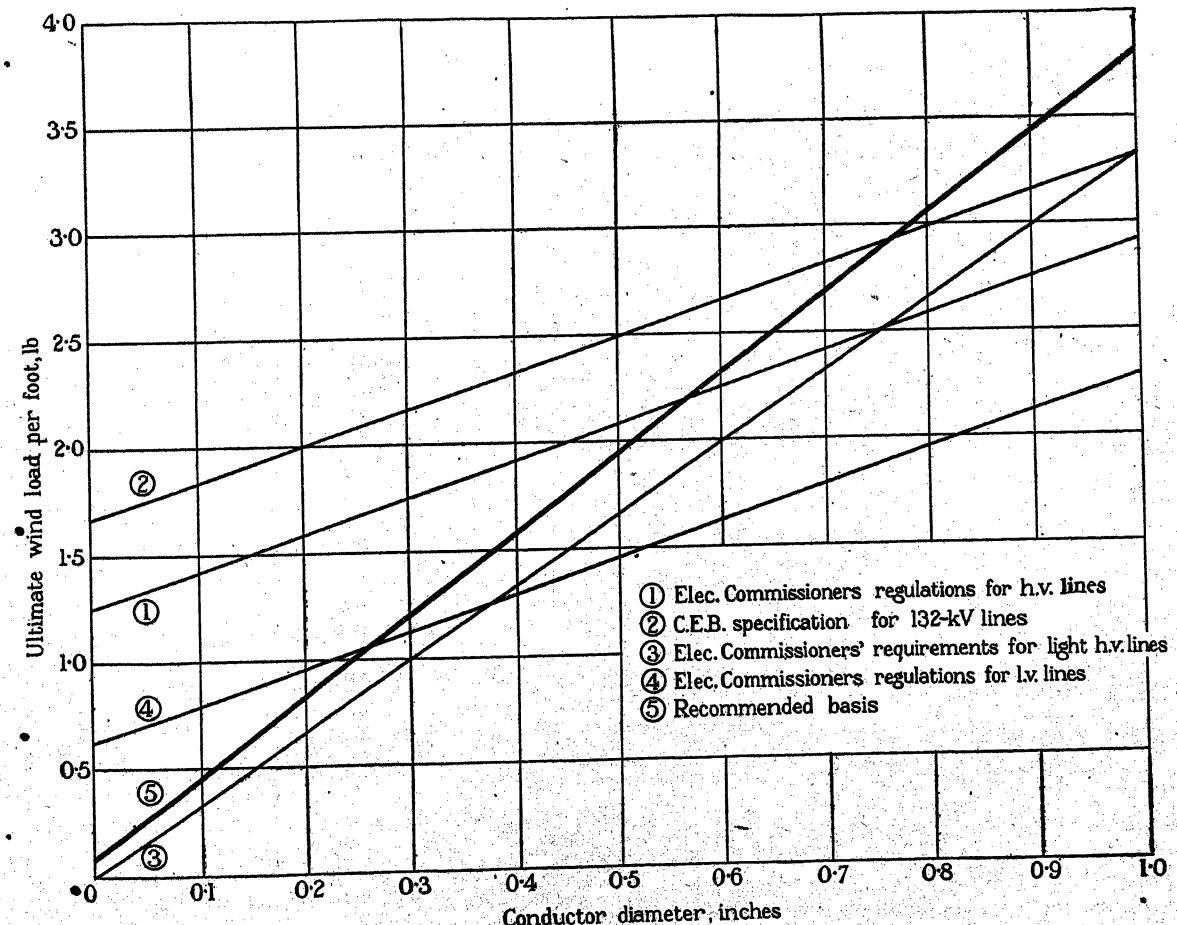


Fig. 9.—Ultimate wind loads on supports.

In Cases 1–4, the working loads have been multiplied by each of the two factors of safety in present use, namely $2\frac{1}{2}$ and $3\frac{1}{2}$. For the case of supports at present required to have a factor of safety of $2\frac{1}{2}$ a comparison between present practice and the authors' proposals is shown graphically in Fig. 9. The ultimate wind loads which the supports are required to withstand without failure or permanent distortion are plotted against conductor diameter. It will be seen that for small conductors the authors' proposals result in a reduction in the wind load transmitted to the supports, whereas there is a tendency for this to increase on large conductors. The comparison would, of course, be similar in the case of supports at present required to have a factor of safety of $3\frac{1}{2}$.

It is recommended that for supports for low-voltage lines which do not exceed 50 ft in height the effect of wind on the supports themselves shall be ignored, but that for all supports to which services are attached, or may be attached in the future, an addition of, say, 250 lb shall be made to the ultimate transverse load, such addition being subject to the same "loading factor" as the other loads.

The method of dealing with the actual wind pressure on supports for other classes of line needs to be defined, but this is a straightforward matter and does not present difficulty.

(4) CONCLUSIONS

The conclusions to be drawn from the paper may be summarized as follows:

1. There is a need for a standard notation and a generally accepted procedure for dealing with sag problems, on the lines advocated in the paper. As a further aid to computation, the standard form of calculation sheet shown in Fig. 10 is recommended. The equation quoted [equation (3) in the paper] reduces to the form $(K_1/T_2)^2 - T_2 = K_2$, where K_1 and K_2 are known. The determination of T_2 by trial and error is greatly facilitated by the use of a slide rule. A rough approximation must first be made by inspection, when K_1/T_2 may be set on the lower scales and $(K_1/T_2)^2$ read direct on the top scale. The assumed value of T_2 is then deducted and the result compared with K_2. The process is repeated until agreement is reached. The importance of a standard method of calculation cannot be over-estimated, as, apart from greater speed of

Physical properties

Equivalent area of copper	in²
Material	
Size and stranding	
Overall diameter	in
Area (A)	in²
Breaking load	lb
Modulus of elasticity (E)	lb/in²
Coefficient of expansion per deg. F (α)	
Weight per ft	lb

$\sqrt{\left(\frac{EA}{24}\right)} = C_1$

$\alpha EA = C_2$

Loading conditions

Radial thickness of ice	in
Wind pressure per ft²	lb
Basis of wind calculation	
Weight per ft, no ice	lb
Wind per ft, no ice	lb
Resultant per ft, no ice	lb
Weight per ft, with ice	lb
Wind per ft, with ice	lb
Resultant per ft, with ice	lb
Maximum tension	lb
Temperature range	deg. F
Normal span length	ft
Basic span length	ft
Basis of sag calculations	

$$\left(\frac{C_1 w_2 l}{T_2}\right)^2 - T_2 = \left(\frac{C_1 w_1 l}{T_1}\right)^2 - T_1 + C_2 t$$

where T_1 = tension under load w_1
t = rise in temperature above initial conditions

Sags and tensions

Initial temp.	w_1	T_1	t	w_2	l	$C_1 w_2 l$	$\left(\frac{C_1 w_1 l}{T_1}\right)^2$	$C_2 t - T_1$	R.H.S.	T_2	Sag			Final temp.

Fig. 10.—Form for calculating tensions and sags.

working and simplicity generally, the chances of error are reduced to a minimum.

2. The procedure for dealing with complete lines involves a number of complications which call for the introduction of approximations based on a thorough understanding of the whole problem. Consideration should be given to the desirability of treating all lines, including those supported on pin-type insulators, as freely supported lines.

3. The authors recommend that the expression "factor of safety" should not be used in connection with overhead lines and that the Electricity Commissioners' Overhead Line Regulations should be amended as follows:

(*a*) The tension in a line conductor shall not exceed three-quarters of its breaking strength when subjected to an ice load of radial thickness $(1{\cdot}6d + 0{\cdot}05)$ inches at 22°F and a wind pressure of 8 lb/ft^2 on the ice-coated conductor.

(*b*) Supports shall be required to withstand without failure or permanent distortion the loads imposed on them when the conductors are subjected to the loading described above multiplied by a loading factor of 2 in the case of wood poles or 4/3 in the case of other types of support. For low-voltage lines, supports required to carry services shall also withstand an additional load of 250 lb, in the direction of the service, multiplied by the appropriate loading factor. The wind pressure on the supports themselves shall be allowed for on a suitable basis, except for low-voltage line supports not more than 50 ft high, in which case it may be ignored.

4. The proposals made in Paragraph 3 above apply to all classes of line as minimum requirements for Great Britain or for countries experiencing similar weather conditions. For the tropics or other regions where ice loading does not occur, the problem is somewhat different, as it may be possible to determine with reasonable accuracy the maximum wind loads that will ever be experienced.

5. The sagging of conductors on low-voltage lines should be based on a maximum still-air sag of 3 ft 6 in on a 180ft span, in accordance with the curves given in Fig. 8.

6. It is urged that if the authors' recommendations for revised regulations be adopted, they should be accepted for all lines, including all crossings of roads, railways, rivers, canals, etc.

7. The paper does not deal with suspended cables, or combined Post Office and low-voltage distribution lines, and these cases may call for separate investigation.

(5) ACKNOWLEDGMENTS

The authors wish to thank Messrs. Callender's Cable and Construction Co., Ltd., and their Chief Engineer, Mr. P. V. Hunter, C.B.E., for permission to prepare and present this paper.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 8TH DECEMBER, 1943

Mr. P. J. Ryle: With regard to the transverse loads applied to angle supports due to the conductor, I agree with the authors that formula (7) should be used, Variations have from time to time been suggested to allow for the supposition that the direction of the wind cannot simultaneously be normal to both spans. At first sight this seems logical, but it may lead to still further complication. First, it is not generally agreed how the wind pressure normal to a conductor varies with the obliquity of the wind to the conductor, and, secondly, if account is taken of the effect of such obliquity it becomes necessary to consider also the difficult case of the wind normal to one span and very oblique to the other. This sets up awkward unbalances, including unbalanced longitudinal loads on the pole. Consequently, I think that formula (7) is the only one for practical design work.

It is however quite possible for the wind to be normal to two spans at the same moment. I have often observed from hills in the Lake District, looking down on a tarn below and watching the ripples caused by the wind, that even at points only 500 ft or so apart the direction of the wind may vary by anything up to, say, 60 deg. The directions of motion of snowflakes in a gale also make this self-evident.

In Section (3.2) the authors say that the direct effect of wind pressure on the supports is seldom of much importance. I do not entirely agree, for with steel towers the overturning moment due to the tower wind is sometimes about 20–30% of that due to the conductor wind. In any case, the effect of a 90–100 m.p.h. gale on the bare line must be borne in mind, as even on a wood pole the transverse load is then quite appreciable compared with that on the conductors.

The authors point out, for the first time I think, the very inconsistent position we have reached in our regulations for the assumed loads on conductors. The Electricity Commissioners' Regulation for ordinary h.v. lines is ⅜in ice and 8 lb/ft^2 wind pressure, but under the new "light" line regulation proposals the ice is abitrarily taken off altogether and the wind pressure increased to 16 lb/ft^2. As the authors point out, any general assumption of small ice thickness is quite illogical, and apart from statutory safety margins the matter really boils down to practical engineering economics. Nature never concerns herself whether the line is "light" or "heavy," and, ignoring all regulations, she may pile on 3–4 in of ice, a state of affairs for which nobody could economically allow. The authors propose to allow for Nature's vagaries in a more consistent way than at present allowed for in our designs. It might be argued that the assumed ice thickness should be a function of the importance and therefore (roughly) of the capital cost of the line, but that would of course be impracticable. Instead of referring to ice at all, would it not be better merely to specify vertical and horizontal loads of some function of *d*, as, I believe, the Germans do?

For large conductors, modern practice is tending towards fixing sags and tensions chiefly from the point of view of avoiding vibration fatigue. On this basis the important feature is what I call the "everyday" tension, i.e. the actual tension in a conductor for probably 98% of its life under more or less still air conditions at 40 or 50° F. Under this tension the stress in the conductor should not exceed some fraction—about 1/5 or 1/6—of the ultimate strength, depending on the material of the conductor. For large conductors, such a basis leads generally to adequate but not excessive margins of safety under maximum loading conditions of the order of ½in ice and 8 lb/ft^2 wind pressure.

In this connection Fig. 9 is rather deceptive; Curve 2 for the C.E.B. 132-kV lines ought to stop at about 0·6in diameter, since smaller sizes are not used for 132 kV.

I am glad that the authors have not recommended a variation of the assumed ice or wind depending rigidly on the part of the country or the height above sea level. In the last 15 years, the blizzard conditions which have caused trouble have often occurred in the least "exposed" areas in the south of England; the only disastrous ice loading in the North-East Coast district was in the lowest and flattest parts of that area.

Mr. E. T. Painton: Different ways of specifying the basic loading are used in different countries, but in nearly every case the specification reduces to a figure which is directly proportional to the conductor diameter. One exception is the German system of basing the load on the square root of the diameter. In no country is the basic loading proportional to the square of the

diameter, yet that is really what the authors now suggest, for they propose that the thickness of ice shall increase with the diameter; and hence the weight of ice must be a function of the square of the diameter. The accumulated experience of every country appears to be against their suggestion.

I think we should bear in mind that, in fixing any basic loading, we are really taking a chance on the weather. It is agreed by the authors that the thickness of ice which forms under any particular conditions does not increase as the conductor diameter increases, so that the basic load is solely a measure of the probability of breakdown within a given period. If we design on a 2in ice thickness, for example, the risk of breakdown due to bad weather will be very small, irrespective of the conductor diameter. With a smaller ice thickness the risk increases, but with any selected thickness there will be no greater risk of breakdown with a large conductor than with a small one. Therefore what justification can there be for saying that if I use copper conductors the basic loading shall be $\frac{3}{8}$in of ice, but if on the same line I use cadmium copper I must design on a larger thickness, and with steel-cored aluminium a larger thickness still? What the authors really want to do is to increase the loading factor, and therefore reduce the risk according to the *importance* of the line; they have been misled into judging the importance of the line by the diameter of the conductor.

The authors dislike the term "factor of safety" as used in the present Regulations; it is true that if a line is designed with a nominal factor of safety of 2 on a $\frac{3}{8}$ in ice basis it could withstand more than twice that load without breaking. They give a method of calculating the actual load to break a conductor, but this assumes the constancy of the modulus of elasticity, i.e. they assume that the total stretch of a copper conductor up to the breaking load is only 0·3%, whereas we know that it is between 1·5% and 2%. The actual load to break the conductor will be much larger than that calculated by the authors' method. In short, our nominal factor of safety of 2 corresponds to an actual factor of safety of 10 or more. It is interesting that the real factor of safety decreases as the conductor diameter decreases, so that it would be logical to base our design on a uniform ice loading for all conductors and to reduce the nominal factor of safety for a larger one.

As regards the conductor tension, I argue that weather conditions which load the conductors up to $\frac{3}{4}$ of the breaking load would not ruin them. They would, however, be stretched to such an extent that the whole line would have to be re-strung. This could be avoided if the elastic limit were increased to 75% of its ultimate strength, but that would involve excessive pre-tensioning.

Mr. H. W. Grimmitt: When stringing, conductors should be pre-stressed before finally making-off. The authors dismiss this necessary precaution purely on account of cost. It is difficult to produce evidence in support of this, but I am sure there has been less trouble with pre-stressed conductors than with those which have not been pre-stressed.

Mr. Painton suggests that when they reduced the radial thickness of ice from $\frac{3}{8}$ in to $\frac{3}{16}$ in the Commissioners were influenced purely by the question of cost. That is not so. In practice it was found most unsatisfactory to string small conductors, i.e. below 0·04 in^2 copper, with tensions calculated on a $\frac{3}{8}$in-ice basis. The tension in the conductor at normal temperature was so very low that the conductors blew about in the breeze. It is wrong to assume that a constant radial thickness of ice is satisfactory for all sizes of conductors. A radial thickness of $\frac{3}{8}$ in is quite satisfactory for conductors from 0·075 up to 0·125 in^2. Seven years' experience has been gained of small conductors strung to $\frac{3}{16}$ in ice and exposed to very bad weather; these lines have proved satisfactory and reliable.

It is obvious that the Commissioners' Regulations do not give a sufficient loading for the larger conductors, i.e. above 0·15 in^2. This has been borne out by the C.E.B. using a $\frac{1}{2}$in radial thickness of ice with a factor of safety of 2·2. The C.E.B. have now gone a step further and based the stringing of the Grid conductor on a maximum sag of 27 ft at 122° F for a 900-ft span. This increase was undoubtedly influenced by vibration trouble.

The value of the authors' paper is the attempt to rationalize the design of overhead lines, and I suggest that they have achieved their object. The paper also draws attention to the uselessness of the present $\frac{3}{16}$in ice load in the Commissioners' Regulations for low-voltage lines. No one in this country erects lines to this loading, and unfortunately most people when erecting low-voltage lines do so without sag/tension charts.

In Fig. 9, curve 2 should stop at 0·6 in diameter as Mr. Ryle has pointed out, and the lower curve No. 3 should stop at 0·3. For conductors between 0·05 in^2 and 0·125 in^2 copper there is a big discrepancy between the recommended ultimate wind load per foot and the Commissioners' Regulations. The difference decreases as the conductor size approaches 0·125 in^2. This means that much lighter supports can be used than hitherto. Judging from the experience accumulated in this country with light lines and also with some war-emergency lines which are extremely light and are operating satisfactorily, I think that this reduction is perfectly safe.

Mr. G. W. Preston: I agree that the authors' method of calculation is as accurate, from the practical point of view, as the use of the catenary formula, but I am not sure it is necessary to have a standard method of calculation, and I see no reason why those accustomed to use the catenary method should not continue to do so.

With regard to pre-stressing, I agree with Mr. Painton that the authors' statement that the erection sags should be reduced "by an amount up to, say, 10%" does seem a little vague. I think a much more scientific method would be to determine for each type of conductor the permanent elongation obtained when the conductor was subjected to the maximum load. When calculating erection sags the permanent elongation which might be expected could then be subtracted from the length of the unstretched conductor, as is done in America.

In Section 3.3 the authors say that "overhead-line design procedure should take account primarily of the external loads necessary to increase the internal stresses to their extreme limits with only secondary regard to the stresses produced at other conditions of loading and temperature." I am not sure that the authors have not concentrated a little too much on the maximum loading without giving sufficient consideration to the tensile conditions at other periods. I see that according to the authors' curves the No. 8 S.W.G. conductor in a 200ft span has about 30·8% of its ultimate tensile stress at 122° F, which is something like 46% at 60° F. That is a rather high tension for very long periods, judging by experience obtained elsewhere. In one of the American safety codes, the tension for rural lines is limited to 25% of the ultimate at 60° F for single-wire, 7- and 19-strand conductors and to 30% for 3-wire conductors, the maximum erection tension at 60° F not being allowed to exceed 35% on any conductor. I feel that we should not concentrate too much on the maximum loading conditions but should also take into account normal operating tensions.

The authors refer to possible damage of the conductor if it is loaded to more than 75% of its ultimate strength, but I am not sure that in the case of copper conductors it is correct to say that beyond 75% the conductors will almost certainly suffer permanent damage as far as their ability to carry further load is concerned. The 0·1% proof stress of hard-drawn copper is at least 83% of its ultimate strength.

Mr. J. R. Harding: The first part of the paper is an extremely useful summary of the sag calculations required in designing and setting out overhead lines, and although the forms of the final equations in Section 2 are not those employed by all engineers they are at least as convenient as any.

To derive the full benefit of the standard notation and form of calculation sheet proposed by the authors, it would be of great advantage if some co-ordinating body, possibly the British Standards Institution, could collect and publish sag calculations and tables for the conductors commonly used in this country and incorporate with these a model form of calculation sheet and the standard physical constants of the materials extracted from the respective B.S. specifications. Engineers who have collected their own data based on their own methods might then be tempted to adopt these standards for future calculations. If this is not done, the advantages claimed at the end of conclusion 1 (Section 4) for a standard method are in effect an inducement to each engineer to adhere to his present method and collected data as affording a useful check on fresh calculations.

I support the authors' emphasis on the factors listed in Section 1 which limit the degree of accuracy attainable in practical sag calculations, to which they add the uncertainty as to the degree of freedom of support to be assumed for both pin and suspension insulators. I support their recommendation that both should be treated as freely supported and that pre-stressing of conductors should not be adopted. Since the non-elastic stretch of conductors results in an increase of length, and therefore corresponds in effect to a permanent increase of temperature, it would seem logical and convenient to allow for this factor, when necessary, by specifying that the conductor be erected to a sag corresponding to a temperature which is a fixed amount below the actual temperature.

Section 3 gives a clear picture of the problems associated with ice loading and the proposed modification to the Regulations is developed logically from the argument, but the curves in Fig. 7 seem to show that there would be little practical advantage in making the change. The reduced erection tensions recommended for the larger conductors are obtained in practice, when required, by adopting $\frac{1}{2}$in ice loading, and the increased erection tensions for the smaller conductors under the relaxed Regulations correspond reasonably closely to those on the recommended basis. I can see no justification for the work involved in calculating a new range of resultant loads for the proposed variations in thickness of ice.

If any change is made I would prefer a simplification by adopting a small thickness of ice for all conductors and varying the factor of safety with conductor diameter to the equivalent extent in a convenient number of steps. I agree that some such term as loading factor would, however, be more accurate than factor of safety.

Mr. J. W. Tubb: For calculating conductor sags, surely it is desirable to adopt an exact method when it exists and not add another inaccuracy, however slight, to those already existing. Hitherto most engineers have adopted the parabolic formula because it is simple to solve. The catenary method has not been used so readily because of the difficulties of arriving at and solving hyperbolic expressions, yet once the catenary equations have been converted to engineering terms, and this has been done for us, accurate results for all span conditions can be obtained more quickly with less mathematical effort than by the other method.

In Table 1 the authors suggest that one should fix a maximum equivalent span and make this the basic equivalent span for the whole line. I agree with this in principle, providing the span lengths throughout the line do not vary too much.

In the last paragraph of Section 2.2.5 the authors suggest that the practice of pre-stressing conductors during erection is to be deprecated, principally on account of cost. I disagree with this point of view, particularly with regard to primary lines. It is not costly, and, where composite conductors are concerned, having regard to the difference of modulus of elasticity between the steel core and the aluminium, when a line is pre-stressed and then let down to its correct sag there is certainly a reduction in the proportion of stress carried by the aluminium. This is very desirable in the light of vibration fatigue fractures. I do not agree with the suggestion of allowing, say, 10% undersagging to save the trouble of pre-stressing.

I agree with the authors that it is very difficult, and perhaps useless, to define a factor of safety when this is based on the unpredictable, namely the weather, ice loading, etc., but I find it difficult to reconcile their suggestion that "the loads be specified to produce in the conductors three-quarters of their ultimate stress;" in other words, a definite factor of safety of $1\frac{1}{3}$.

Fig. 6 suggests striking a mean between all the agreed conditions for ice and wind loadings by adopting a straight-line law. This law would cause the ice loadings to vary with the conductor diameters and would restrict the freedom of choice for lines run in areas of varying geographical and meteorological conditions.

The paper does not refer to conductor fatigue failures caused by vibration at normal temperature. Some significance has been attached to this trouble on certain lines, and the conductor tension in still air at 40° F made the principal feature of the sag calculation.

I suggest that a model specification be prepared giving a maximum value for erection tension at a normal temperature of, say, 40° F, together with the maximum permitted span for each conductor throughout the range of conductors in use, in preference to a factor of safety that we are trying to avoid.

Mr. W. J. Nicholls: I support the standard form of sag calculation table in Fig. 10. In Section 2.2.6 reference is made to sag templates and an example is given, but there is no suggestion that the profile scale should be standardized. I think it would be of considerable help if it were standardized at the figures given in this example.

With regard to paragraph (*c*) of Section 3.4, where there is a reference to the C.E.B. maximum sag of 27 ft on a 900ft span, it should be made clear that this sag was increased from the 22 ft used on the original Grid solely to avoid vibration troubles, and, so far as ice and wind loading is concerned, experience has shown the 22ft sag to be satisfactory.

With reference to the factor of safety and the authors' suggestion of 75% of the ultimate load, we should differentiate between such widely-varying materials as aluminium and cadmium copper by considering a loading which, I believe, the Germans use and which they call the permanent tensile strength of the conductor. This is the maximum tensile strength which a conductor will resist for one year without breaking, and is determined for each material.

As to ice loading, I am afraid the author's formula is a little unfair to certain conductors. For a large-diameter conductor of steel-cored aluminium this formula gives a large amount of ice as compared with a pure copper conductor of the same capacity. I suggest that, instead of building up the load from the weight of ice and the wind pressure, we should go straight to the load in pounds per foot of conductor. For example, we might take the total load on the conductor, including its own weight, as twice the weight plus $\frac{1}{2}$ lb/ft run. This would give a loading which for 0·175 in^2 conductors is very slightly less than that given by $\frac{1}{2}$in ice plus wind, and for medium conductors is almost equal to the loading of $\frac{5}{8}$in ice plus wind, while for small conductors it falls to a little over $\frac{1}{2}$ lb/ft.

Dr. H. G. Taylor: The factor of safety was referred to in the paper read by Mr. Burke* in December last, and there was considerable divergence of opinion in the discussion. The present authors have been very discreet in saying that they think "factor of safety" is not an appropriate term to apply to overhead lines, but I am not sure that they are talking about the same thing as Mr. Burke, because they say that it is a fallacy to assume that a fixed factor of safety implies a constant margin of strength, whereas I think it does. I understand "strength" to mean stress. If the authors mean by "strength" load, then I agree that they are right.

I am concerned at the emphasis which has been laid on the ice coating on the overhead line, since this is not the only factor. There are also the windage and the reduction of temperature, and if we adhere to "factor of safety" we can take account of all three. Incidentally, I am surprised that in such discussions as these no one ever thinks of a temperature of less than 22° F, which, after all, is not particularly low for this country.

On the question of maximum permissible stress I find that Mr. Boyse has changed his point of view since the discussion on Mr. Burke's paper. Then he thought copper should not be stressed to more than half its breaking load; now he thinks it can be stressed to $\frac{3}{4}$ of the breaking load. A number of different suggestions on this point are available. Mr. Burke in his paper suggested 90% of the ultimate tensile stress, i.e. a factor of safety of 1·1. The present authors propose 75%; i.e. a factor of safety of 1·33, under different conditions of ice loading. The Electricity Commissioners propose 50%, i.e. a factor of safety of 2, with $\frac{3}{8}$ in ice at 22° F. I maintain that one can continue down that scale; in fact, we have done so to some extent in the case of the relaxed conditions of the Electricity Commissioners where the ice loading is left out altogether and the factor of safety is 2·5 with wind loading only. I would go still further than that. I see no logical reason why a larger factor of safety should not be assumed under a more lightly-loaded condition.

In the discussion on Mr. Burke's paper I compared three loading conditions, the first being the condition suggested by Mr. Burke, the second the normal condition, and the third a condition with a factor of safety of 4 at 74° F. The sag curves corresponding to these conditions were arranged to give the same sag for a normal conductor of 0·1 in^2 at a span of 350 ft and I drew attention to what seemed to be distinct advantages in the third loading condition. [Dr. Taylor here drew a sketch on the blackboard.] It will be noticed that in the diagrams in the bottom row in Fig. 7 the tension curve is practically flat, where the Electricity Commissioners' Regulations are used, but the authors' suggestions give a much more sloping curve. The result of having a steep loading curve is that there is a big difference in tension on the two sides of a section tower. In diagram (j) in Fig. 7 there is about 700lb difference of tension per 100ft difference of equivalent span on the two sides, which corresponds to 2 tons for six conductors. In diagram (m) in Fig. 7, where the disparity is greatest, for a difference of 100 ft the difference in tension is 3 tons. I think that is very important indeed. If we refer to the sag curve, we see that in diagram (m) the authors' curve goes up very steeply, which indicates that on the long spans there is much greater sag and therefore a much greater risk of clashing with conductors, and to avoid this it is necessary to have much greater spacing in addition to taller towers. On a 1 000ft span the sag is increased from 20 ft to 35 ft. That seems to be a very serious disadvantage, and occurs to some extent in all the curves which the authors show. Another disadvantage is that on the shortest spans there are more likely to be vibration difficulties.

* "Some Problems in Transmission-Line Design" (see 1943, 90, Part II, p. 158).

Mr. C. H. E. Ridpath: In Section 3.4 there is a reference to the formula evolved by the British National Committee of the I.E.C. That formula was finally approved in its provisional form at the meeting of the I.E.C. at Scheveningen in 1935. I think it is important because it was intended to be a basis for International Regulations and assumes a total loading which increases as a linear function of the diameter, whereas the authors suggest a formula which increases the load as the square of the diameter. This loading must result in a large increase in the cost of supports, and it must be very carefully examined, with the experience amassed so far, in order to see whether the extra loading and extra cost are really justified. We can do that by examining certain cases where there have been heavy ice loads.

I have one case in mind, namely the 132-kV line of the Grampian Electricity Supply. That line operates in Scotland at altitudes of over 1 000 ft and presumably the wintry conditions are fairly severe. This conductor was strung in accordance with the Regulations to which the Grid was originally made to conform, that is, $\frac{1}{2}$ in ice, a wind pressure of 8 lb/ft^2 and a factor of safety of a little over 2. That corresponds to a maximum of still-air sag of 22·4 ft, whereas the authors' proposed sag in Fig. 6 works out at 27 ft. I have confirmed that during its 13 years of life this conductor has stood up to the wintry conditions of those altitudes in such a way that there has been no question of increasing the factor of safety. I think cases like that must be considered when the authors' suggested loading is examined.

In the much-discussed chart given in Fig. 6 the position of the top part of the curve is fixed by this particular point, i.e. 27 ft sag on 900 ft at 122° F, and from the paper it appears that this was so because the sag had been determined by experience gained under ice-loading conditions, but I understand now that it was due to the possibility of vibration trouble, which is obviously a different matter altogether (especially as vibration trouble can be eliminated by suitable dampers). It appears therefore that, as far as the larger sizes of steel-cored aluminium are concerned, the location of the top end of the curve is not justified and hence the necessity for the resulting heavy loading has not been proved.

Mr. A. Burke (*communicated*): In Table 1 the authors summarize "the correct procedure" which, I agree, enables the Regulations governing minimum ground clearance and maximum tension to be exactly satisfied. Their method, in the case of free supports, is acceptable for lines which are unlikely to be affected by vibration and for those lines to which dampers are fitted. But for lines with the larger sizes of copper conductors and rather short spans their method leads in some cases to an undesirably high tension under everyday conditions.

The authors rightly state that it is desirable to specify a superimposed load corresponding to the highest possible stress, but they add that a conductor will almost certainly suffer permanent damage if it is stressed to more than 75% of its ultimate strength. On what data do they base this conclusion? Copper conductor will withstand a stress of 75% of its ultimate strength continuously for over a year, but S.C.A. is not so good. Hence, on the authors' assumption of a 10-yearly heavy loading, it should be permissible to take a higher figure than 75% for copper—perhaps as high as 90% as suggested in my paper. No final decision should be made without carrying out extensive tests on all types of conductor, and the necessity for doing so is not obviated by taking a conservative figure of 75%, since the correct figure varies with the material. The authors' second difficulty (regarding the modulus of elasticity) is simply solved by the method in my paper.

As regards the actual loads, the specified minimum thickness of ice should be the same for all sizes of conductor and its value should be such as would give the minimum permissible degree of safety in the smaller sizes of conductor when used on the maxi-

mum economic equivalent spans for these sizes. Undoubtedly this would permit much tighter stringing for the larger sizes than on existing lines, but the designer would be free to select a lower tension in order to ensure freedom from vibration trouble or to get a higher degree of safety commensurate with the importance of the particular line. These latter questions should not be controlled by statutory regulations and in fact the Electricity Commissioners' Overhead Line Regulations are "for securing the safety of the Public." Hence the authors are proposing an (undesirable) innovation when they suggest that these Regulations should be revised in accordance with their formula for ice loading, which is clearly based on economics and not on public safety, in the case of the larger sizes of conductor.

A radial thickness of ice of 0·31 in at 75% of the ultimate strength is far too low for 0·02 in^2 copper conductor. In other words a 400ft span is too long for this conductor when erected in accordance with the Electricity Commissioners' relaxed Regulations; a suitable limit is 300 ft.

Mr. A. C. Fielding (*communicated*): It appeared from a superficial consideration of the proposed series of parabolic templates that an interval between successive members of the series equivalent to, say, 6 in on the sag of a 500ft span might be satisfactory for setting out a profile on level ground, but that the difference between the slopes of successive templates at the tops of 3 000–4 000ft spans might seriously limit the usefulness of the proposal. It is so frequently necessary, even on a line of comparatively short spans, to use a template covering very long spans in order to plot the conductor profile on sloping ground, that any considerable error in the slope at the extremities of the template would produce unacceptable inaccuracies in setting out. Calculation of a typical example shows, however, that the danger is not serious. Assuming that one template represents on a 400ft span a sag of 5 ft and the next template a sag of 5 ft 6 in, the corresponding slopes of the sloping 400ft spans between the ends of a 3 200ft and a 4 000ft span are approximately 78° and 79° on a template with vertical and horizontal scales of 1 in to 20 ft and 200 ft. This indicates that, with comparatively coarse steps between successive standard templates, the errors introduced by the use of the standard template nearest to the theoretically-correct template will not be serious. It will be interesting to know the range of templates which the authors propose.

Modification of the existing Regulations is most desirable, but the revised Regulations should be simple and should obviously be an improvement on the present ones. The statutory $\frac{3}{8}$in radial ice irrespective of the size of conductor is supported by observation of the actual thicknesses of snow or ice carried by conductors of different sizes under similar abnormal conditions. In south-west England and in South Wales during the snowstorm of February, 1933, the thicknesses of snow on P.O. lines and on 0·77in dia. conductors were more nearly equal than in proportion to the conductor diameters. That a uniform ice coating affects most seriously transmission lines employing small conductors is a feature common to structures and plant of many types; the smaller the unit the more heavily outside conditions affect the design. The only logical reason for reducing the loading of less important lines is that of commercial risk and expediency, but the assumption that the less important lines are those with small conductors is not a valid generalization. In the initial preparation of a scheme, a choice has frequently to be made between a line with a small conductor and a lower voltage line with a big one. It would therefore seem logical when modifying the statutory ice or equivalent loading to introduce a factor to represent the importance of the line. The factor might be the product of the area of the conductor and of the voltage or be otherwise related to the designed loading capacity of the line. A linear relation between the conductor diameter and the thickness of ice appears to conform neither with the loading encountered in practice nor with the grading of the load to suit the importance of the line. This is surely a problem for the Electrical Research Association.

Mr. J. P. Harding (*communicated*): In Section 4 the method given for the determination of T_2 involves setting up on the slide rule K_1/T_2, squaring this, deducting T_2 and comparing the result with K_2. Two constants K_1 and K_2 are thus involved and an initial division K_1/T_2. Using the nomenclature of the paper, a slight simplification can be made by expressing equation (3) in the form—

$$T^2(T - T_0) = (C_1\omega L)^2 \quad . \quad . \quad . \quad . \quad (1)$$

Suffix 1 applied to both T and ω will give the relationship between these quantities under initial conditions; suffix 2 gives the same relationship under final conditions.

This equation can be solved for T_0 with the slide rule. It can be shown that T_0 is actually the tension which would exist at zero loading. This may be visualized as that occurring in a wire of zero or negligible weight, or in a wire of finite weight if the points of suspension be assumed to be lowered to ground level while being maintained the same distance apart. T_0 may be positive or negative and will, of course, depend on the temperature. A negative tension indicates that the wire must be under compression to assume the length between supports. A positive tension indicates that the wire would still be under tension when relieved of all load.

The change in T_0 for a rise in temperature of θ deg C is $- C_2\theta$, where $C_2 = \alpha EA$, as in the paper.

Thus
$$T_\theta = T_0 - C_2\theta \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If, therefore, values of T and ω are given, the value of T_0 may be found from equation (1). Correction for temperature can then be made by equation (2). Equation (1) is used finally to ascertain the tension under the changed loading conditions.

Since the authors recommend that a conductor should not be stressed to more than three-quarters of its breaking load under the most adverse conditions assumed, it may be more convenient to use equation (1) in the form below:—

$$f^2(f - f_0) = C_3(\omega L/A)^2 \quad . \quad . \quad . \quad . \quad (3)$$

where f is the stress in the conductor, and C_3 is $E/24$. Suffix 1 or 2 may be applied to f and ω as stated for T and ω in equation (1).

I support the authors' criticism of the term "factor of safety" and its use as a basis of calculation; it should be replaced by a term such as "load factor at yield," being the ratio of that load which produces a tensile stress equal to the nominal value of the yield of the conductor to the maximum design load.

On this basis, the authors' recommendation to permit conductors under maximum design load to reach within 75% of their ultimate breaking load would be equivalent to a "load factor at yield" of unity, assuming that the yield point of the conductor was at 75% of its ultimate load. Thus, whilst a satisfactory margin of strength relative to failure may be obtained, there will be no margin relative to yield. Due to inaccuracies in erection, the conductor may, under maximum design loading, reach a tension beyond its yield point, suffer permanent set and require restringing.

It is suggested that a "load factor at yield" of between 1$\frac{1}{4}$ and 1$\frac{1}{2}$ would be appropriate and avoid this difficulty. Alternatively, the stress in the conductor under maximum load could be limited to about 90% of its yield stress. Equation (1) represented graphically (Fig. A) shows clearly the connection between T and ω, and brings out the discrepancy between the "factor of

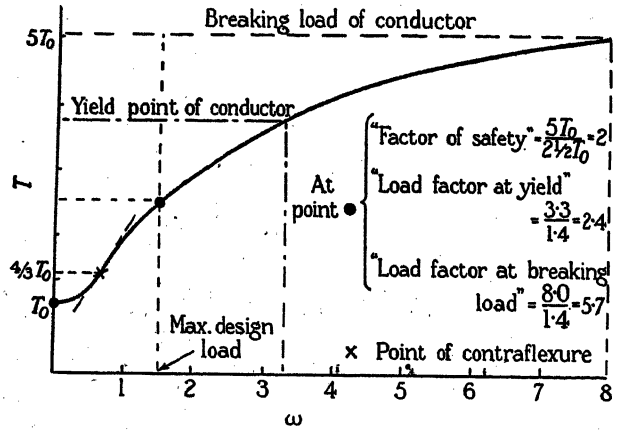


Fig A

safety" as commonly assumed and the proposed "load factor at yield." It can be shown by successive differentiation that the T, ω curve contains a point of contraflexure at $T = (4/3)T_0$ and that the slope of the graph $dT/d\omega$ at $\omega = 0$ is zero. This is of particular importance in the calculation of stringing tensions for aerial cables, since a small superimposed load such as the load of the suspension strand itself will produce only a very small increase in the tension T_0. Thus, with very close approximation, the stringing tension of the suspension strand of an aerial cable may be taken as T_0 (the weightless tension), which considerably simplifies the work of design.

Mr. G. W. Molle (*communicated*): I think the authors will agree that the real limiting factors on the erection tensions applied in practice are connected more with the stability of angle and terminal supports, and of stays, than with weather conditions. It would not be a practical proposition to erect conductors at the tensions permitted by the Regulations: the ironwork and insulators at terminals and heavy angles would not stand it.

It does not seem to be generally appreciated that the "ice-loading" specified in the Regulations has nothing to do with *actual* ice. It is intended to limit, artificially, the tensioning of the smaller conductors and to ensure that conductors are not strung to tensions where vibration troubles are experienced. For these reasons ice-loading should be applied in the design of conductors erected in the tropics; I found in India that it was not a practical proposition to string conductors to the tensions calculated on wind loading alone.

Some years ago, I investigated actual weather conditions in this country over a period of 50 years. Severe conditions may be expected once in 10 years, and a blizzard in which ice loading and 60–80 m.p.h. wind occur simultaneously, about once in 30–40 years. Notable winters occurred in 1880, 1916, 1927 and 1939. In 1939–40 I saw solid ice of 1¼in diameter on conductors of all sizes for miles on end. Some l.v. 4-wire conductors failed under ice load alone and P.O. lines and poles collapsed for miles.

Ice loading in mountainous parts of this country has been known to exceed 3½ inch diameter on conductors, causing collapse of power lines: very rarely a gale occurs in such conditions; but usually with ice-forming conditions the wind velocity is under 12 m.p.h. Ice may be solid (57 lb/ft^3) or packed-snow (specific gravity about 0·1). In the U.S.A., ice is prevented by passing a current of 300 amp or so through lines to keep the temperature above freezing-point.

I am convinced that actual erection tensions used in practice allow a very large margin of safety as regards mechanical failure of conductors. I would welcome a paper from the authors' wide experience, dealing with the stability of line-supports, pole foundations, and stays.

Mr. H. R. S. Preston (*communicated*): The authors' proposed loadings on conductors are not as consistent as implied, and the figure of 75% of the conductor ultimate strength would not, I am sure, be used for calculating the stresses on angle and terminal supports. Conductor tension at normal temperature is one of the main factors which decide whether broken wires occur under vibration conditions; therefore this tension is of paramount importance. Because the tension in the 37/·11 S.C.A. Grid conductor was reduced at 40° F in still air from a factor of safety of 5·14 to 6·9, the authors have based their proposals for conductor loadings on this higher factor of safety for all types of conductors —composite and homogeneous—which is an unsound and unreasonable assumption because the tensile strength of the material should be considered. Their proposal does reduce the loadings on the smaller conductors, but to such an extent as one could definitely assert that vibration troubles would result.

For h.v. supply, up to 11 kV, single wood-pole lines would continue to be used with span lengths of 240-500 ft. The following Table gives the factors of safety of various conductors at 40° F in still air, if erected to the authors' proposals.

Conductor	Equiv. copper cross-section	Factors of safety at spans of				
		240 ft	300 ft	360 ft	400 ft	500 ft
Copper	in²					
No. 8 S.W.G. ..	0·02	2·2	3·1	4·5	5·5	
3/·094 in	0·02	3·3	5·6	7·6	8·5	
3/·104 in	0·025	2·8	4·5	6·4	7·3	
7/·086 in	0·04	2·0	2·4	3·2	3·8	
3/·147 in	0·05	2·2	2·8	3·9	4·6	
7/·136 in	0·1	1·7	1·9	2·2	2·5	3·3
S.C.A.						
7/·093 in	0·025	2·2	3·1	5·3	7·7	
7/·132 in	0·05	1·9	2·4	3·3	4·4	
7/·076 + 7/·173 in	0·1			2·1	2·3	3·4
Cadmium copper						
3/·105 in	0·022	1·7	1·9	2·2	2·5	3·9
3/·112 in	0·025	1·6	1·8	2·1	2·4	3·5
7/·103 in	0·05	1·5	1·6	1·7	1·7	2·0
7/·146 in	0·1				1·6	1·8

I suggest that supply authorities should be asked to report all lines on which broken wires due to vibration trouble have been found and to state the span length and bases of sag calculations, etc., so that the minimum permissible factor of safety on the ultimate strength at 40° F in still air may be obtained. It is to be hoped that such a questionnaire would enable a stipulated minimum factor of safety to be decided and incorporated in the revised Regulations, which would then include the worst conditions of loading and also the minimum factor of safety at 40° F, and whichever was the worse condition should apply to sag calculations.

As a relaxation for unimportant lines for conductors up to, say, 0·04 in^2 equivalent copper, the stipulated factor of safety at 40° F could be the basis of sag calculations, the maximum span being limited. These factors of safety, I suggest, may be: copper conductors, 3½; cadmium conductors, 3½; S.C.A., 7.

Mr. G. S. Sloan (*communicated*): I agree with the authors in preferring the use of the parabola to the catenary as a basis for sag and tension calculations. The slightly greater accuracy of the catenary formulae is of no practical importance, compared

with the other sources of inaccuracy in the design and erection of a transmission line.

The error introduced by taking the average pin-insulator wood-pole line as flexible, and using the equivalent span method of calculation is quite small. Taking, as an example, a 3-phase line with pin insulators, 0·075in^2 copper conductor, wood poles 29 ft over ground and 8in top diameter, and considering a straight run consisting of four 100yd spans and one 200yd span, I have calculated that, if the line is sagged on one of the 100yd spans at 15° C and the conditions change to − 5° C and 1 in radial ice the actual tension under the new conditions does not differ from that calculated by the equivalent span method by more than 5½%. In the calculation it is assumed that there is no slip in the binding at the insulator and no movement of the pole in the ground, only deflection of the pole above ground being considered.

I am glad to see that the authors disagree with the common, but rather ineffective practice of pre-stressing conductors during erection. A reference to Fig. E of Mr. Burke's reply to the discussion on his paper shows that, for copper, pre-stressing to any load less than the maximum to be expected in service is useless. We have found that if a length of stranded copper conductor is loaded up to about three-quarters of its breaking stress, then unloaded and allowed to rest for some time, a further non-elastic stretch occurs when it is once again stressed to the previous load.

The authors refer to the "normal" value of the modulus of elasticity. I should be interested to know what value they accept as "normal" for stranded copper. Tests we have carried out have all given, even after repeated loading to three-quarters breaking stress, a value of the modulus, calculated from the straight portion of the stress/strain curve, of less than that given in reference books, namely 18×10^6 lb/in^2. The authors are not justified in using the normal value of the modulus of elasticity for a range of stress up to three-quarters breaking load. Our tests on an 80yd length of 0·075in^2 stranded copper gave a value for this modulus in the stress range from one-quarter to three-quarters breaking load of about 75% of that obtained for the range from one-quarter to one-half.

The authors recommend that their revised regulation should be applied to crossings of roads, railways, rivers, canals, etc. Would they say what would be the effect on the engine if a train ran at high speed over a conductor, copper or steel-cored aluminium, lying across the tracks?

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. C. O. Boyse and N. G. Simpson (*in reply*): Our reply to some of the principal points raised by several speakers can be conveniently given under the following heads:

Limiting Conductor Tension.—In suggesting that sag calculations should be based on 75% of a conductor's ultimate strength, our chief concern was to select the maximum stress up to which the conductor could indefinitely resist loading cycles corresponding to weather changes. The ratio of this stress to the ultimate will vary somewhat with the material of the conductor, and an exact definition of limiting stress may be needed. At the same time, the "endurance limit" in the German Regulations VDE/0210/1936 seems appropriate, and as stated by Mr. Nicholls, this is the maximum stress that a conductor will withstand for one year. Some typical values taken from the VDE Regulations expressed as percentages of the tensile strength are: copper, 75%; bronze, 80–88·5%; aluminium, 66·7%; steel, 73·80%. A reasonable average of these figures is obviously 75%. In our opinion, the slightly greater accuracy obtained by varying the ratio for different conductors is not worth while, in comparison with the general simplification obtained by using a constant figure.

Wind and Ice Loading.—Our proposed ice-thickness formula has been criticized as revolutionary on the ground that the ice thickness should be the same for all conductors. Yet the present Overhead Line Regulations, which in all main principles have been in force for nearly twenty years, give a similar result to our own formula. Although these Regulations prescribe a constant ice thickness on all conductors at half breaking load, it is obvious from Fig. 5 that the ice thickness to raise the tension to ½ of breaking varies greatly, not only with span length, *but also with conductor diameter.* This is also borne out by Fig. 6 in which the ice thicknesses show a very pronounced increase with conductor diameter.

We do not claim that the expression for ice thickness $(1 \cdot 6d + 0 \cdot 05)$ in is necessarily a perfect solution to the problem, but we do maintain that the theoretical basis from which it is derived is the correct one, and that further study of the subject on the lines advocated should be made by a representative committee. Various alternative proposals have been made during the discussion and these deserve further examination. We are not opposed to the use of a fixed ice thickness for all conductors at ½ breaking load, but this might lead to bigger sags on small conductors and smaller sags on large conductors than under the present Regulations. We agree, too, that conductor diameter is not a perfect measure of the importance of a line.

Several speakers have drawn attention to the reason for the 27ft maximum sag on C.E.B. 132-kV lines. It is true that this arose because of vibration trouble rather than on account of wind or ice loading, and if vibration should be ignored for fixing wind and ice loads the right-hand end of the straight line on Fig. 6 could be lowered appreciably. This, however, must be considered in conjunction with the next paragraph.

Everyday Tensions.—The tension in a conductor at an average temperature, in still air or a light wind, may be of considerable importance from the point of view of vibration trouble, but it has no other special significance. Nevertheless, we agree that the everyday stress in a conductor should be limited, but we think that this can be done by a suitable choice of wind and ice loading. The only alternative, indicated by Mr. H. R. S. Preston, is to consider the two conditions and to work to the one giving the bigger sag. This should, however, be avoided if possible, owing to the extra work involved in making sag calculations.

Pre-stressing.—There are two admissible reasons for pre-stressing conductors after erection but before sagging: (1) to eliminate inelastic stretch, and (2) to control the distribution of stress in composite conductors. At present information on the effect of any given pre-stressing on either inelastic stretch or stress distribution is inadequate. The E.R.A. are working on this problem, and pending their report we are not in favour of arbitrary pre-stressing.

The determination of the permanent elongation for each type of conductor could be undertaken, as suggested by Mr. G. W. Preston, and the results would prevent, with greater accuracy than at present, the encroachment on ground clearance resulting from inelastic stretch. In the meantime, we think it best to adopt the approximation recommended in the paper. Mr. J. R. Harding's proposal that inelastic stretch should be expressed as a correction to the erection temperature is excellent.

Detailed Replies to Various Speakers.

Mr. Ryle.—We do not recommend neglecting the wind pressure on supports, except with low-voltage line supports not more than 50 ft high. We therefore agree with Mr. Ryle on this point.

We had already considered the possibility of specifying con-

ductor loads as some function of d, but think it desirable to preserve a sense of practical values by retaining ice thickness and wind pressure, so that in districts where particularly severe conditions may be expected suitable allowances for extra ice or wind may more readily be made. Once a mathematical expression for load has been adopted, a 10 or 20% variation has no real meaning in terms of ice thickness and wind pressure.

Mr. Painton.—Mr. Painton implies that the resultant of wind and weight loading, which we propose, is proportional to the square of the conductor diameter, whereas it is only the weight of ice which varies roughly in this way. The wind component is proportional to the first power of the diameter.

Mr. Painton is not correct in assuming that the factor of safety, in the sense in which he uses it, is proportional to the total stretch of a conductor at breaking, and in any case the stretch of 1·5–2%, which he quotes, refers to a 10in length. The corresponding figures for a drum length or even a single span are much less. Equation (9) for calculating the actual load to break a conductor does assume a fixed modulus of elasticity, and we realize this leads to a slight inaccuracy. But it is absurd to suggest that the results given by the formula are of the order of one-fifth of the correct values. It is only the first term on the right-hand side of equation (9) which is inversely proportional to the modulus of elasticity, and as the span length increases this term becomes rapidly smaller.

Mr. Grimmitt.—The "sloppiness" on small conductors resulting from the application of $\frac{3}{8}$ in of ice at half breaking load has already led to provisional changes in the Regulations, and the satisfactory experience gained therefrom is further justification for the reduced ice thicknesses which we advocate for small conductors. We hope that Mr. Grimmitt's remarks about low-voltage lines will encourage engineers to adopt the erection sags given in Fig. 8.

Mr. J. R. Harding.—We welcome the suggestion that the B.S.I. might publish sag calculations and tables incorporating a model form of calculation sheet on the lines we have advocated. Possibly a B.S. Code of Practice for this subject could be drawn up to include such further recommendations as the method of dealing with complete lines and the treating of all lines as freely suspended.

Mr. Tubb.—A serious disadvantage of Mr. Tubb's plea for the catenary method of calculating sags is that it requires access to tables or curves before any results can be calculated.

Mr. Nicholls.—We should like overhead-line profile scales to be standardized, which, in effect, resolves itself into a choice between horizontal scales of 1 in = 200 ft and 25 in = 1 mile.

Dr. Taylor.—Our attitude to the whole question of factors of safety and maximum permissible stresses is based on the fundamental principle that it is necessary to start from the amount of superimposed load which will increase the stress in a conductor to the extreme limit. This is directly opposed to Dr. Taylor's suggestion that a large factor of safety should be provided under a light load. We do not consider that unbalanced tensions at section supports are objectionable. Such supports are spaced at large distances and can be designed to resist whatever loads may be imposed upon them, without appreciably affecting the cost of a complete line.

Mr. Ridpath.—We agree that the I.E.C. British National Committee's Memorandum provides an excellent basis for comparing the Regulations of various countries. The adoption of the British formula at the 1935 meeting was, however, provisional only, on the understanding that the study of the formula should be extended to certain factors not previously considered. We do not agree that the loading of supports proposed must result in a large increase in cost. This is apparent from Fig. 9.

Mr. Burke.—Mr. Burke puts forward a plausible case for a constant thickness of ice for all conductors, but admits that the selected thickness would be appropriate to the smallest conductor only. This procedure would largely destroy the practical value of any Regulations by giving too much licence to the ill-informed designer, and it is doubtful whether it would meet with the approval of the Electricity Commission.

Mr. Fielding.—We did not suggest the construction of a series of sag templates to cover all cases, as Mr. Fielding appears to infer, although this is an excellent idea. The procedure we visualized was to make templates for all jobs, as required, until so many had accumulated that an existing template could usually be found suitable for a new job. On the use of sag templates for sloping spans, we think it follows that, if the maximum permissible error is governed by a level span where the curvature is a maximum, the errors on sloping spans where the curvature is less will also be less.

Mr. J. P. Harding.—Mr. Harding describes a method of approach to sag calculations which is of some academic interest, and which taken step by step gives the same results as our equation (3) provides in one operation. His definition of T_0 is misleading, as a suspended weightless conductor must be under zero tension. It is only with catenary wires for the suspension of heavy cables that T_0 represents a reasonable approximation of the stringing tension.

Mr. Molle.—We do not agree that the stability of angle and terminal supports is the limiting factor in the determination of conductor sags, except in the case of low-voltage lines, or on lines containing such a large proportion of angle supports that they have an important influence on the cost. All our calculations of ice deposits are based on ice weighing 57 lb/ft^3.

Mr. H. R. S. Preston.—We do not understand Mr. Preston's suggestion that angle and terminal supports would not be designed to resist $\frac{3}{4}$ of the breaking strength of the conductors. We have proposed multiplying $\frac{3}{4}$ of the breaking strength of the conductor by a "loading factor" of $\frac{4}{3}$ giving an ultimate tension of unity applied to the supports. This compares favourably with the present practice of multiplying $\frac{1}{2}$ breaking load by a factor of safety of $2\frac{1}{2}$, which gives an ultimate tension on the supports of 1·25.

Mr. Sloan.—Mr. Sloan and Mr. J. R. Harding are both in favour of treating pin insulator lines as freely suspended, and in the absence of any arguments to the contrary we think the case for this procedure has been made. All our calculations for copper conductors are based on a modulus of elasticity of 18×10^6 lb/in^2. We have had no experience of railway engines running over conductors.

ELECTROMAGNETIC AND MECHANICAL EFFECTS IN SOLID IRON DUE TO AN ALTERNATING OR ROTATING MAGNETIC FIELD

By ROBERT POHL, D.Eng., D.Sc., Member.*

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INTRODUCTION AND SUMMARY

A problem still awaiting solution is the complete predetermination of the phenomena connected with the penetration of alternating flux into solid iron. It arises in the design of such increasingly important machines as electromagnetic clutches and eddy-current brakes, solid-rotor induction motors and self-starting synchronous motors, and also in recently perfected industrial applications such as surface hardening. The classical expressions[1, 2] for the flux and current distributions and the iron loss due to an alternating m.m.f. rest on the assumption of constant permeability and therefore apply only to values of induction far below those now employed. Moreover, they ignore hysteresis, which will be shown to affect both the loss and the power factor to such an extent as to invalidate these expressions for practical purposes. A further difficulty arises in machine design, in that the m.m.f. acting upon the iron surface forms an unknown component of a known primary m.m.f.: a second component is absorbed in flux paths outside the iron and depends on the magnitude of the total flux.

The object of the paper is to present this subject to the designers of electrical machines in a manner with which they are familiar and to advance it, in addition to discussing the connection between the primary ampere-turns and their surface component, by showing and including in simple expressions the effects of hysteresis, and by extending the theoretical and experimental investigation to values of induction beyond the knee of the magnetization curve. So far, only the theoretical boundary case of ideal saturation[3, 4] has been solved, and it will be shown that a computation based upon a given magnetization curve of the iron is possible by means of a graphical method.

Section 2, "Practical Applications," deals with the utilizable mechanical effects in various types of machines and indicates means for improving their performance. It may be read without special reference to Section 1.

(1) THEORY. ELECTROMAGNETIC EFFECTS

(1.1) The Vector Diagram. The Interrelation of Currents and Induction in the Iron

The primary ampere-turns per pole (AT_p) are assumed to be a sinusoidal function of time. They will generally be stator ampere-turns, the stator being separated from the surface of the solid rotor by an air-gap of known length. We may, in the usual way, treat AT_p as forming a radially directed m.m.f. The induction of a flux and of currents in the solid iron is a transformer effect. The resultant of all such secondary currents, the secondary ampere-turns per pole AT_s, must be determined before the penetration phenomena can be approached. AT_s may be obtained by a vector diagram, Fig. 1, which is similar to that of a current transformer having a considerable magnetizing current. The vector $AT_p = AB$ has not only to balance the vector $AT_s = CB$ but also to supply the magnetizing ampere-turns per pole $AT_m = AC$. The point C lies on the arc of a circle such that AT_p subtends the peripheral angle $90° + \psi$, where ψ is the angle between AT_s and the e.m.f. E, which lags 90° behind the flux Φ_p and AT_m. The angle ψ depends on the properties of the secondary circuit which are so far unknown. For given values of AT_p and ψ the diameter of the circle remains the same for all values of AT_m. A change of this vector causes C to move along

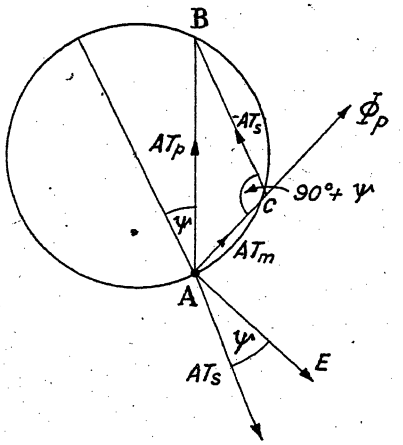


Fig. 1

the circle, and if AT_m becomes negligibly small C moves to A, AT_m and Φ_p become tangential, and AT_p and AT_s become equal in magnitude and opposite in sense.

The very small depth of penetration into the solid iron makes the circumferential part of the flux path of chief interest. It is therefore preferable to operate with tangentially magnetizing ampere-conductors and the tangential flux $\Phi = \Phi_p/2$. We may refer the former to the length of circumference they occupy by dealing with ampere-conductors per centimetre or, briefly, amp/cm. These we express by the symbol N. Fig. 1 may thus be drawn with N_p, N_s, N_m instead of AT_p, AT_s, AT_m, and with Φ instead of Φ_p.

To find N_s for a given N_p we must know N_m and ψ, which involves knowing Φ and the reluctance which N_m has to overcome. We shall consider first the reluctance for N_m and the phenomena in the iron, and we shall show later how to obtain Φ and ψ. Let all lines of Φ, Fig. 2, be linked with all primary conductors. The solid secondary part of the "current transformer" has an infinitely large number of circuits in the different layers. In Fig. 2

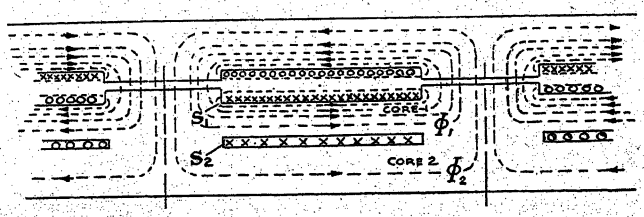


Fig. 2

only two such circuits, S_1 and S_2, are indicated as conductors in a laminated core. The first represents the surface layer. Its current I_{S_1} is induced by the total flux Φ, which divides itself into Φ_1 through core 1, and Φ_2 through core 2. The second circuit S_2, which is at a greater depth, is influenced only by Φ_2, i.e. by all lines below S_2. Since S_1 and S_2 have different inductances, I_{S_1}

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and I_{S_2}, Φ_1 and Φ_2 are not in phase with each other. As long as core 1 remains unsaturated and the magnetic potential difference across its ends is very small, only a small flux Φ_2 can exist in core 2 with a correspondingly small current I_{S_2} in S_2, since any such current I_{S_2} is a counter-current tending to oppose Φ_2 and to force the lines through core 1. Φ_2 and I_{S_2} will make their appearance in proportion to the rise of a magnetic p.d. across core 1, the latter always balancing the m.m.f. of I_{S_2}.

Applied to a solid secondary we can say: the induction B_x at any depth x within solid iron is due to a m.m.f. equal in magnitude and opposite in direction to that of all currents at a greater depth. The resulting m.m.f. of all secondary currents thus balances the magnetic p.d. along the surface. It follows that our magnetizing component N_m has only to be large enough to drive the flux through its path outside the induced iron, i.e. through primary iron paths and the air-gaps to the surface on either side of core 1 in Fig. 2. The magnetic reluctance of the "secondary" iron does not affect N_m as long as an inner core in the iron remains unsaturated. It is clearly far easier to determine Φ, and thence N_m and N_p, from a known or assumed value of N_s, than to begin with N_p. We shall therefore first assume values of N_s, and find and plot Φ and N_p as functions of N_s, and from the curves derive the desired effects for any given value of N_p.

In this sense, we now assume N_s amp/cm acting along the iron surface, to be known. Dropping the subscript s for the further treatment we shall call its amplitude $\hat{N}$, its r.m.s. value N, and its instantaneous value $n(= \hat{N}\cos\omega t)$. For the magnetic quantities no r.m.s. values are needed: the symbols Φ and B denote amplitudes. At the depth x below the surface the active amp/cm are $n_x = \hat{N}_x\cos(\omega t - \psi_x)$. The assumption that the induced currents resulting from a sinusoidal primary source are also sinusoidal ceases to be correct when the knee of the magnetization curve is reached. A rigid analytical solution can be given only on the assumption of constant permeability, i.e. by taking the part below the knee as a straight line. For the higher part we shall have to be content with a graphical approach.

(1.2) Flux and Current Distribution. Eddy-Current Loss, Total Flux and Power Factor. The Influence of Hysteresis

(1:2.1) B Below the Knee of the Magnetization Curve. Analytical Solution with and without Hysteresis.

Section 5.1 gives an easy derivation of Thomson's fundamental equation applied to solid iron, and Section 5.2, a close parallel to it, the modifying effect of hysteresis, both for the simple case of constant permeability. The effects at the depth x produced by a surface m.m.f. in amp/cm $n = \hat{N}\cos\omega t$, without regard to hysteresis, may be expressed by

$$n_x = \hat{N}\epsilon^{-mx}\cos(\omega t - mx) \quad . \quad . \quad . \quad . \quad (1)$$

whence also

$$b_x = B\epsilon^{-mx}\cos(\omega t - mx) \quad . \quad . \quad . \quad . \quad (2)$$

where

$$m = \sqrt{(\pi f c/\rho)10^{-8}} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$c = B/\hat{N} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and ρ = resistivity in ohms per cm cube.

Equation (1) shows the exponential decrease of $\hat{N}_x = \hat{N}\epsilon^{-mx}$ which, reversed, is the vector sum $\hat{I}_x$ of all induced currents in depths greater than x. It also shows the "spiralling" due to their phase angle growing with mx. The induction $b_x = cn_x$ follows the same law. Its surface value is not affected by induced currents.

We shall now derive the chief quantities needed in designing, and contrast them with the form they assume when hysteresis is taken into account.

Equation (1) leads at once to the current densities in the iron $g_x = \frac{\partial n_x}{\partial x} = -\frac{\partial i_x}{\partial x}$, to the eddy-current loss, and also to the flux. Writing $g_x = \hat{N}\epsilon^{-mx}m[\sin(\omega t - mx) - \cos(\omega t - mx)]$,

$$g_x = -\sqrt{2}m\hat{N}\epsilon^{-mx}\cos(\omega t - mx + \pi/4) \quad . \quad . \quad (5)$$

and the surface value

$$g = -\sqrt{2}m\hat{N}\cos(\omega t + \pi/4) \quad . \quad . \quad . \quad . \quad (6)$$

Therefore $G = -\sqrt{2}mN$

$$\boxed{\psi = \pi/4 \mid \cos\psi = 0{\cdot}707} \quad . \quad . \quad . \quad . \quad (7)$$

In Fig. 1, the angle ψ, whatever the values of f, c and ρ, is now seen to be 45° because G, in phase with E, is $\pi/4$ ahead of $-N$, the resultant of all secondary currents corresponding to AT_s. G and E are in phase because we found E from the sum of all the lines linked with the surface, so that $E = \rho G$. In practice, as shown below, the angle ψ is much smaller than 45°, owing to hysteresis.

The eddy-current loss per square centimetre of iron surface, which will be designated l_e, is found by taking the r.m.s. value of g_x, i.e. $G_x = -\sqrt{2}mN\epsilon^{-mx}$, and calculating $\rho\int_0^\infty G_x^2 dx$, which gives

$$\boxed{l_e = \rho m N^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The resultant flux Φ is found from the surface e.m.f. $e = \rho g_0 = -(d\phi/dt)10^{-8}$ which it produces. We have by integration $\phi = \rho\sqrt{2}\frac{m}{\omega}\hat{N}\sin(\omega t + \pi/4)10^8$, whence

$$\phi = \frac{c}{m}N\sin(\omega t + \pi/4) \quad . \quad . \quad . \quad . \quad (9)$$

with the amplitude

$$\boxed{\Phi = (c/m)N} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

As a check on (8), it may be noted that the loss ρmN^2 is equal to the induced power $EI\cos\psi$ since

$$E = \rho G = -\rho\sqrt{2}mN, \qquad I = -N, \qquad \cos\psi = 1/\sqrt{2}$$

Where the lines of force leave the "secondary" iron for the "primary" part, as shown in Fig. 2, two such amounts of flux join together to form the flux of a pole. We may therefore write

$$\Phi_{pole} = 2\Phi l = (2c/m)Nl \quad . \quad . \quad . \quad ? \quad (11)$$

where l is the axial length in cm.

The effect of the hysteresis on the loss in sheet iron at radio frequencies has been discussed by Bethenod,[5] Latour,[6] and Dannatt.[7] The analysis for solid iron at constant permeability reveals very simple laws and is the more needed since the effect of hysteresis proves to be so pronounced as to invalidate the classical expressions for all practical purposes.

To generalize the foregoing equations, we express the hysteresis loss in watts per cm cube of iron at the highest induction B and frequency f by

$$L_h = \eta f B^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

The quadratic relationship is a sufficiently close approximation for our case if η is chosen correctly for a value of B_x equal to about $\frac{3}{4}$ of the surface induction B. For a constant $c = B/\hat{N}$ this implies a constant "hysteresis angle" σ, since we can also write

$$L_h = EN\cos(90° - \sigma) = 4{\cdot}44Bf10^{-8}(B/c\sqrt{2})\sin\sigma$$

whence $\sin\sigma = (\eta c/\pi)10^8$ . . . . . (13)

The fixing of a value for η thus implies a corresponding choice of σ as a constant for the straight part of the magnetization curve. As shown in Section 5.2, the fundamental equations may be easily modified on this basis to include hysteresis. They assume the forms (1*a*), (2*a*) and (5*a*), whence by the same procedure as before (6*a*) to (11*a*) are found; these should be compared with the respective equations (1) to (11).

The hysteresis constant is defined by the term

$$h = \sqrt{(1 + \sin\sigma)} = \sqrt{[1 + (\eta c/\pi)10^8]} \quad . \quad . \quad (14)$$

(1*a*) $n_x = \hat{N}\epsilon^{-hmx}\cos[\omega t - mx\sqrt{(1 - \sin\sigma)}]$

(2*a*) $b_x = B\epsilon^{-hmx}\cos[\omega t - mx\sqrt{(1 - \sin\sigma)} - \sigma]$

(5*a*) $g_x = -\sqrt{2}m\hat{N}\epsilon^{-hmx}\cos[\omega t - m_x\sqrt{(1-\sin\sigma)} + \pi/4 - \sigma/2]$

(6*a*) $g = -\sqrt{2}m\hat{N}\cos(\omega t + \pi/4 - \sigma/2)$

(7*a*) $\boxed{\psi = \pi/4 - \sigma/2 \mid \cos\psi = 0{\cdot}707h}$

(8*a*) $l_e = \rho mN^2/h$

(9*a*) $\phi = (c/m)N\sin(\omega t + \pi/4 - \sigma/2)$

whence as before

(10*a*) $\boxed{\Phi = (c/m)N}$

(11*a*) $\Phi_{pole} = (2c/m)Nl$

The total loss is obtained by calculating $-EN\cos\psi$ which with $\cos\psi = h/\sqrt{2}$ leads to

$$\boxed{l_{e+h} = \rho mN^2 h} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

Therefore $(l_{e+h})/l_e = h^2 = 1 + \sin\sigma$

The following are the main conclusions as to the effects of hysteresis: The "spiralling" of the induced currents, i.e. their increasing lag, becomes less pronounced as expressed by the factor $\sqrt{(1 - \sin\sigma)}$ in equation (1*a*). As a result, since the total induced current I must remain equal and opposite to the impressed N, the eddy-current loss—equation (8*a*)—decreases in the ratio $1/h$. The total loss, however, rises by the factor h and thus becomes $1 + \sin\sigma$ times the eddy-current loss, as was to be foreseen. It should be noted that these relationships under the stated assumption remain the same whatever the frequency. The widely held opinion as to the negligible importance of hysteresis at high frequency is seen to be unfounded. The reason is that the hysteresis loss for a given volume of iron and a given induction proportional to f, is as a whole, like the eddy-current loss, proportional to $\sqrt{f}$, since the depth of iron between the surface and the level at which a given induction is reached decreases with $1/\sqrt{f}$, as proved by equation (2*a*).

The effect of hysteresis on the resulting power factor is very pronounced. As the phase angle falls from 45° to 45°$- \sigma/2$, and as σ is, even for unsaturated mild steel, of the order 30°, the power factor rises from 0·707 to about 0·87, and no doubt even higher for cast iron and other materials with broad hysteresis loops. The increase of the total loss for $\sigma = 30°$ is given by the hysteresis constant $h = \sqrt{1{\cdot}5} = 1{\cdot}22$. As the total flux and therefore the induced voltage, apart from distortion effects, are not influenced by hysteresis [see equations (10) and (10*a*)] both the loss and the power factor for a given N increase to the same extent. In inductor-type machines and other applications where an alternating flux is superimposed on a constant flux, the hysteresis loss may be much increased relative to the eddy-current, as shown by Rosenbaum.[8] This effect would be represented in the present analysis as a larger hysteresis angle.

(1.2.2) **B passes the Knee of the Magnetization Curve. Graphical Determination.**[9]

A graphical method of determining the phenomena in the iron should be based upon the $B/\hat{N}$ curve as used in design offices, i.e. the locus for the apex of the hysteresis loops. First, the fundamental difficulty already referred to, namely the appearance of higher harmonics, must be considered. A sinusoidal n_x wave of amplitude N_x beyond the knee creates a flatter-than-sinusoidal wave of induction b_x. Its highest value is the B_x corresponding to $\hat{N}_x$ on the $B/\hat{N}$ curve. Its fundamental curve (b_{1x}) has a higher amplitude B_{1x}. If the iron has a perfectly horizontal $B/\hat{N}$ curve, we shall get a rectangular b_x curve of height B for which the ratio B_1/B is $4/\pi$. The higher the saturation employed in practice the nearer B_{1x}/B_x will approach this ratio. For any given shape of the $B/\hat{N}$ curve and any value of B_x, B_{1x} may easily be obtained by Fourier analysis, together with B_{3x}, etc. For a given quality of iron, we may once and for all plot B, B_1 and, if needed, B_3 and other harmonics as functions of $\hat{N}$. Fig. 7 shows B and B_1 curves for mild steel. It may be investigated whether, by using the values of B_1 instead of B for graphical construction, we can eliminate the chief difficulty resulting from the curvature of the characteristic. The values of B_1 permit the fundamental values of B_x and G_x on passing beyond the knee to be deduced. Alternatively, the $B/\hat{N}$ curve can be used throughout, ignoring wave distortion. The results of either method can then be compared with those obtained by tests. The problem of harmonics as the sources of loss will be considered later.

The construction of a step-by-step diagram of the flux and current distribution for a given $B_1/\hat{N}$ or $B/\hat{N}$ curve is based on the fact that for any value of x, B_x is due to a m.m.f. equal and opposite to the vector sum I_x of all currents in greater depths, while the current density $G_x = E_x/\rho$ follows for a given value of ρ from an induced e.m.f. E_x and thus from the vector sum of all fluxes at greater depths. Again, hysteresis is at first ignored.

(1.2.2.1) *The Spiral Diagram without Hysteresis.*

Divide the $B_1/\hat{N}$ curve (Fig. 3) into the straight part up to

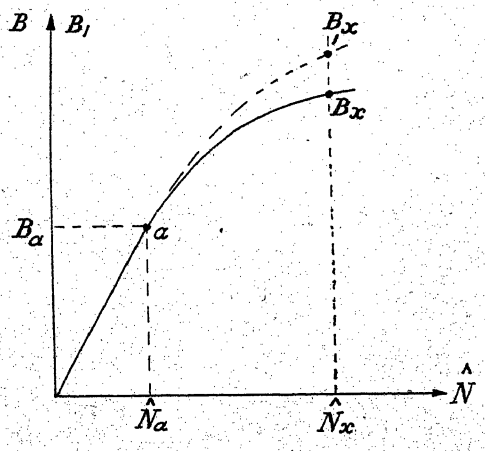


Fig. 3

point a for which $c = B_a/\hat{N}_a \simeq B_{1a}/\hat{N}_a = \text{constant}$ and the curved part with decreasing c. For a primary $\hat{N}$ greater than $\hat{N}_a$ there exists a depth $x = a$ where $B_x = B_a$, so that $\hat{N}_a$ is the effective m.m.f. For this level the values of Φ_a and l_{ea} are obtained by equations (8) and (10). We also know ψ to be 45°.

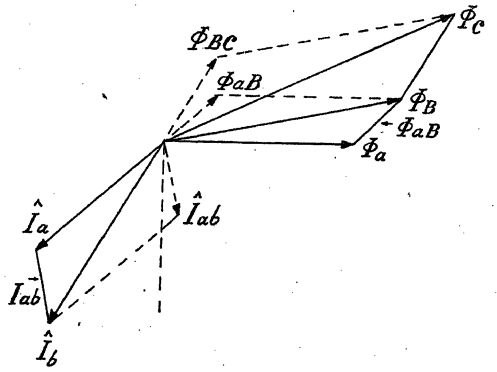


Fig. 4

We can thus commence with vectors Φ_a and $\hat{I}_a$ of Fig. 4 with a phase difference of 90° + 45°.

Now consider the level "a" as the centre line for the lowest of a number of layers AB, BC, CD, DE (Fig. 4A), with a suitable

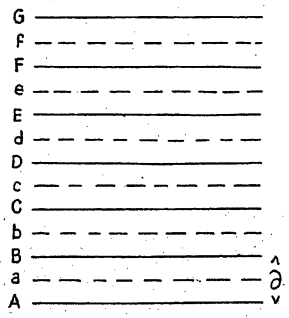


Fig. 4A

thickness of δ. This need not necessarily be the same for all layers. The axes of these layers are a, b, c, d, e.

Now the current density G_B at level B is produced by a total flux Φ_B resulting from the known Φ_a and a flux Φ_{aB} between the levels given by the subscripts. The latter flux, however, is $\partial B_a/2$, if we take B_a as the induction for the layer AB. This flux must be in the same direction as, but of opposite sense to, $\hat{I}_a$, as it is produced by a component $\hat{N}_a$ of the primary ampere-turns which holds $\hat{I}_a$ in balance. Thus in Fig. 4, we may combine Φ_{aB} with Φ_a to Φ_B, noting the changed angle, and find $G_B = (4\cdot44f\Phi_B/\rho)10^{-8}$, and $\hat{I}_{ab} = \sqrt{2}G_B\partial$ lagging 90° behind Φ_B. This combined with $\hat{I}_a$ leads to $\hat{I}_b$, constituting the effective m.m.f. at the level "b." Thus, from the magnetization curve, we have found the mean induction B_b for the layer BC, which gives $\Phi_{BC} = \partial B_b$ in opposition to $\hat{I}_b$. This combined with Φ_B gives Φ_C, and thence G_c, $\hat{I}_{bc}$ and $\hat{I}_c$. Proceeding as before, we get, step by step, the induction values B_c, B_d, B_e for the respective levels, and the corresponding values of $\hat{N}$, Φ, G and ψ, and also of l_e. The latter is easily found by the expression $EI\cos\psi$. The last layer of currents, nearest the surface, is only $\partial/2$ thick.

Any level arrived at in constructing this diagram gives a picture, with an accuracy depending on the ∂ chosen, of the magnetization of the iron in question with a surface m.m.f. corresponding to the value $\hat{N}_x$ for that level. From a single spiral diagram, any desired number of points may therefore be obtained for all the quantities in which we are interested.

(1.2.2.2) *The Spiral Diagram Including Hysteresis.*

To obtain trustworthy results for practical use, modifications to include the hysteresis effects have to be made. First we require to know the hysteresis angle as a function of the highest induction in a cycle of magnetization. This is the angle by which the flux may be considered to lag behind its m.m.f. A hysteresis loop for B (gauss) obtained experimentally, and the corresponding $\hat{N} = \hat{I}T/\text{cm}$, supplies through its area in line-ampere-turns per cm × 10^{-8} the watts per cycle for a cm cube of the iron. Their ratio to $4\cdot44B_1\hat{I}T10^{-8}/\sqrt{2}$ is cos (90°–σ_1), whence σ_1 is found. By taking several hysteresis loops for different values of B, σ_1 may be found and plotted over the whole course of the $B_1/\hat{N}$ curve as a function of B_1. Fig. 8 shows such a curve for mild steel, where σ_1 is seen to fall rapidly beyond the knee. Similarly, a σ/B curve may be obtained from the $B/\hat{N}$ curve, ignoring wave distortion.

These σ curves now enable us to introduce into the spiral diagram the hysteresis as affecting both the loss and the phase angles (Fig. 5). Again, use the diagram of layers in Fig. 4A;

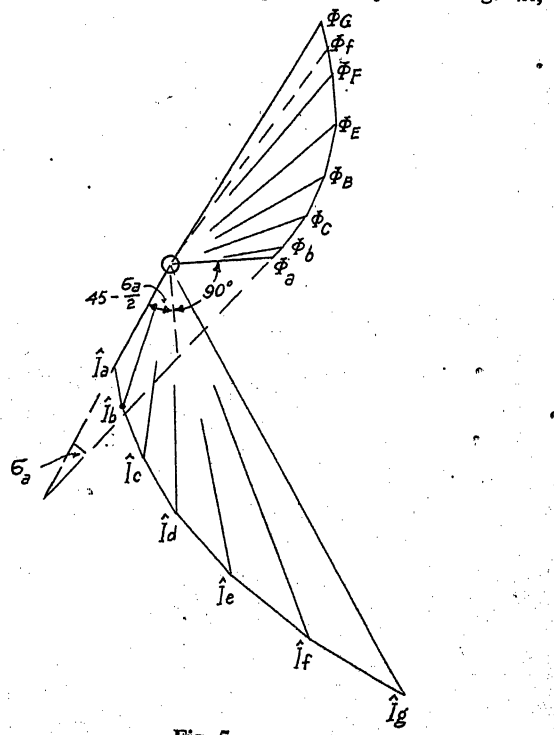


Fig. 5

the initial vectors Φ_a and $\hat{I}_a$ now have a smaller phase difference $90 + 45 - \sigma_a/2$, such that $EI\cos\psi_a$ is the sum of eddy-current and hysteresis losses, namely ρmN_a^2h.

The total flux Φ_B below the level B is the resultant of Φ_a and the flux Φ_{aB} between the levels a and B, namely $\partial B_a/2$. This flux, however, is no longer exactly in opposition to $\hat{I}_a$, but lags by the hysteresis angle σ_a corresponding to the B_a to be taken from the σ curves just discussed. The Φ_B thus obtained supplies the current density G_B and $\hat{I}_{ab}$ which lag 90° behind Φ_B. $\hat{I}_{ab}$ combined with $\hat{I}_a$ gives $\hat{I}_b$, the effective amperes per cm at level "b," and thence B_b, the mean induction for layer BC. The corresponding $\Phi_{BC} = \partial B_b$ is again not exactly in opposition to $\hat{I}_b$, but lagging by the angle σ_{1b}, or σ_b. Proceeding as before, and introducing at every level the respective hysteresis angle, all the values required can be constructed for successive levels. The results obtained, particularly l_{e+h}, Φ and $\cos\psi$, may then be plotted as functions of the surface ampere-turns, as shown in Figs. 9, 10 and 11.

(1.2.2.3) *The Harmonic Currents as Sources of Loss.*

A sinusoidal primary current when the knee of the $B/\hat{N}$ curve is passed implies a non-sinusoidal primary voltage, and vice versa.

The present investigation is based on the former assumption, chiefly for application to star-connected three-phase windings from which triple harmonic currents are excluded. In other applications, however, the assumption of a sinusoidal primary voltage may be preferable to meet practical conditions.

As to the origin of the harmonic loss: primary e.m.f. components of non-fundamental frequency, which we have just recognized as necessarily connected with induced harmonic currents in the iron, cannot transmit power with the sinusoidal primary current. The I^2R loss of such currents can be supplied only from the primary side as the product of the primary sinusoidal current and an e.m.f. component of fundamental frequency. Fig. 6 suggests how the superposition, for example, of a triple-

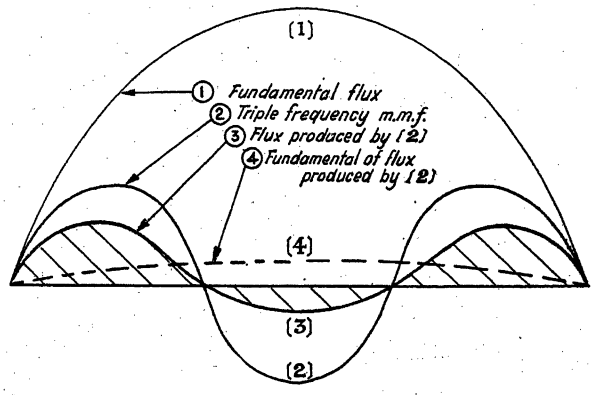


Fig. 6

frequency m.m.f. on a fundamental flux can, owing to saturation effects, create an additional fundamental flux component, which is shown dotted. This phenomenon is similar to that used in frequency-tripling transformers, but reversed.

It must be noted, however, that any fundamental flux component thus indirectly produced will, through the fundamental currents it creates, balance a corresponding primary-current component and thus reduce the amount of directly induced fundamental currents. For practical purposes consideration will therefore be confined to the directly induced fundamental effects, with the proviso that the conclusions thus arrived at require empirical adjustment. A fuller theoretical and experimental study of the complicated interactions between harmonic and fundamental phenomena has not been attempted.

(1.3) Test Results

A mild steel ring of 34·3 cm external and 30·5 cm internal diameter, 1·9 cm thick, with corners rounded to 0·32 cm radius, was fitted with a magnetizing winding of 1 000 turns and, beneath it on the iron, with a shallow winding of 500 turns for measuring the flux and also a thermocouple for recording the surface temperature. The cross-sectional area of the iron was 3·54 cm^2, its surface area 720·3 cm^2 and its mean circumference 101·8 cm. The following tests were taken:—

(1) The specific resistance of the iron at 20° C: $\rho = 0{\cdot}163 \times 10^{-4}$ ohm per cm cube.

(2) The d.c. magnetization curve, i.e. the induction B (gauss) as a function of $\hat{N}$, the ampere-conductors per cm (Fig. 7). The corresponding $B_1/\hat{N}$ curve for sinusoidal magnetization, obtained by Fourier analysis from the $B/\hat{N}$ curve, is also given.

(3) A number of hysteresis loops, from which the hysteresis angle σ as a function of B, and σ_1 as a function of B_1, are calculated (Fig. 8).

(4) Power-factor, flux and loss curves under sinusoidal magnetization up to very high values of $\hat{N}$ (Figs. 9, 10, and 11). To

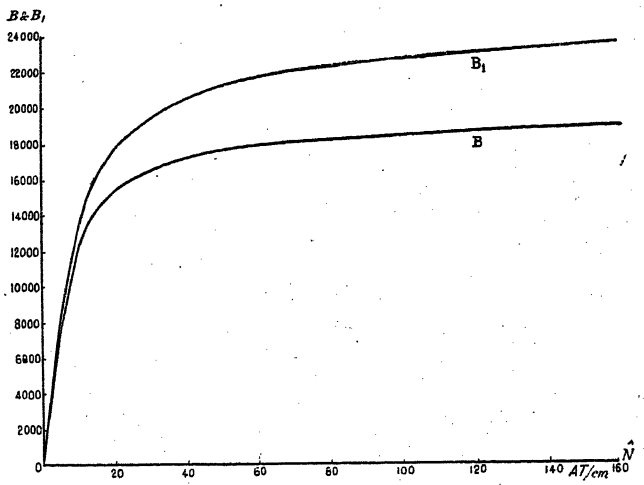


Fig. 7

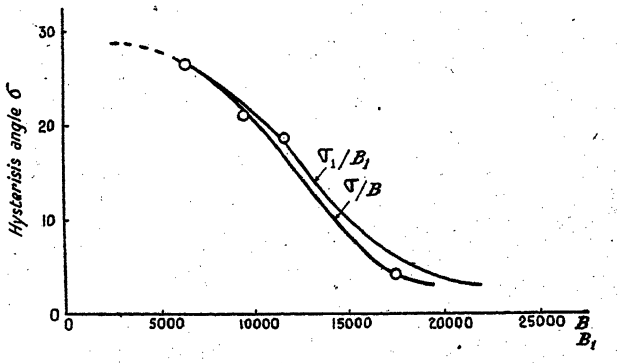


Fig. 8

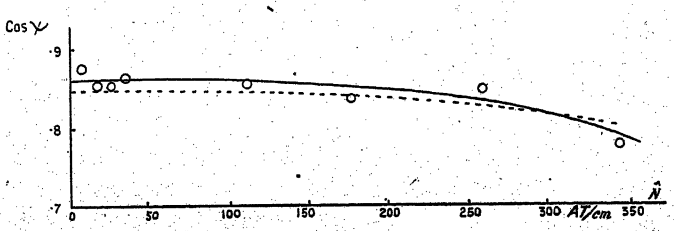


Fig. 9

avoid an appreciable departure from the desired sinusoidal current wave form, the exciting coil was energized from the 400-volt 50-c/s mains through a large non-inductive resistor which absorbed by far the greater part of the voltage. A cathode-ray oscillogram showed no recognizable harmonic, even at the highest excitation. To maintain the specific resistance practically constant, readings were taken quickly and the temperature of the surface was recorded. After every reading the temperature was allowed to fall to room temperature. A mean-reading voltmeter connected across the 500-turn coil was used for measuring the flux. This coil was also connected to the volt coil of the wattmeter.

(5) Oscillograms of the induced voltage, of which Fig. 12 is an example, showing the distortion due to saturation and hysteresis. Fig. 12 applies to $N = 34{\cdot}3$ ampere-conductors per cm. Its shape approaches the theoretical curve given by Haberland[4] for ideal saturation.

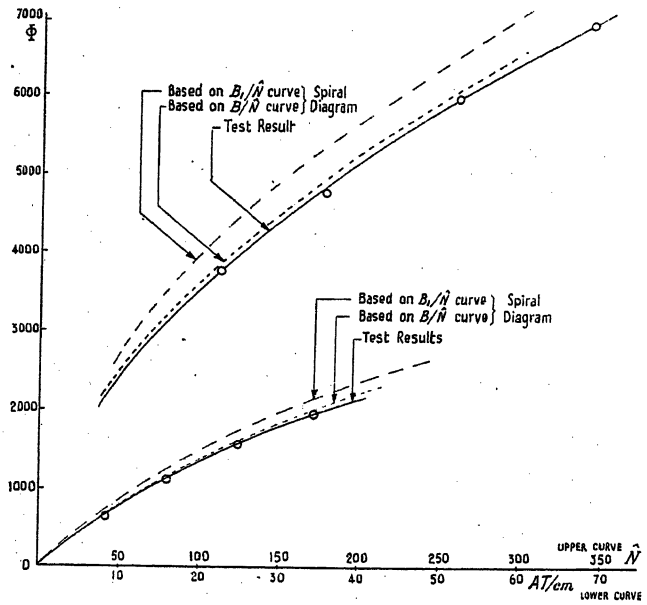


Fig. 10

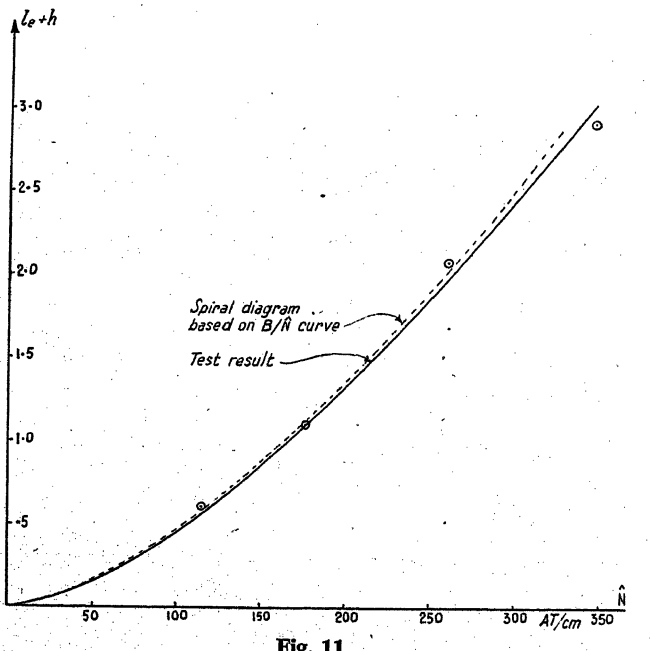


Fig. 11

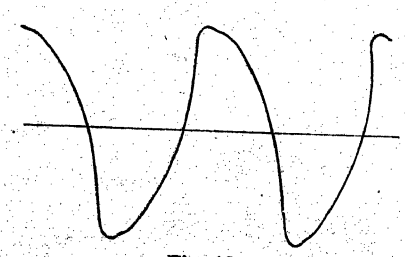


Fig. 12

(1.4) Conclusions

(1.4.1) ***B* remains Below the Knee of the Magnetization Curve.**

The general formulae for the power factor, the flux and the total loss, e.g. equations (7*a*), (10*a*) and (15) are confirmed. Taking $B = 9\,450$ as the highest induction for which c could be regarded as practically constant, and using $\sigma = 26°$ corresponding to $B = 7\,000$ as the appropriate hysteresis angle up to that value, $\cos\psi = \cos(45 - 13)°$ is found to be 0·85, compared with a measured value of 0·86. The flux and the loss also agree within the limits of accuracy of the measurements.

(1.4.2) ***B* passes the Knee of the Magnetization Curve.**

The flux values obtained from a spiral diagram based on the B_1/N and σ_1/B_1 curves show a marked divergence from the test results, as is shown in Fig. 10. The departure of the form factor of the e.m.f. wave from 1·11 is far too small to account for this result. It appears that the replacement of the B/N by the B_1/N curve overstates the influence of the harmonics. The spiral diagram was therefore redrawn on the basis of the B/N and σ/B curves. The values of flux, power factor and loss now obtained agreed satisfactorily with the tests, as shown by the curves in Figs. 9, 10, and 11. Further theoretical and experimental research into the effects of wave-form distortion due to saturation and hysteresis is needed. In the meantime, it appears that where the straight part of the characteristic is passed practical requirements may be satisfied by a spiral diagram based on the B/N and σ/B curves. Its use, though at first rather tedious, enables one to prepare for office use a set of curves for any given material, giving the required quantities as functions of N for the desired range of frequencies.

(2) PRACTICAL APPLICATIONS. MECHANICAL EFFECTS

The reaction between the induced currents and the magnetic fields in the solid iron sets up mechanical forces with radial and circumferential components; only the latter of these are of practical importance. They create the torque in machines employing rotating fields, whether rotation be brought about mechanically as in eddy-current brakes and induction clutches, or by primary windings as in polyphase motors. The flux and current distribution were given by our preceding investigation, and this permits a calculation of the tangential forces by finding the product of the radial component of induction and the current density, and integrating it both peripherally over a pole-pitch and radially over the depth of induction from the surface to infinity. For a sinusoidal distribution of the surface m.m.f. over the pole arc, this procedure presents no difficulties. The result, however, is obtained more quickly and in a more general form by using the previous expressions for the total loss in the iron. The tangential forces of a rotor moving relative to the field with slip velocity must represent a power equal to that loss. Thus a known loss and slip will immediately lead to the tangential force and the torque.

(2.1) The Torque of Induction Motors with Solid Rotors, Induction Clutches and Eddy-Current Brakes

Let a magnetic field rotate relative to a solid rotor of diameter d and length l in cm, with a slip frequency $f_s = sf$, where s is the fractional slip, another frequency $f = np$, p being the number of pairs of poles and n the speed in revolutions per second. The field intensity may be derived from the highest local value, AT_{pole} of the radially-directed ampere-turn wave assumed to be sinusoidally distributed over the pole pitch $\tau = d\pi/2p$. For the usual case of a 3-phase winding, we have the well-known expression

$$AT_{pole} = \left(1 + 2 \times \frac{1}{2}\cos 60°\right)\frac{4}{\pi}\sqrt{2}\, ITf_w = 2{\cdot}7\, ITf_w$$

where I is the r.m.s. value of the phase current, T the number of turns per pole per phase, and f_w the winding factor, i.e. the product of spread factor and pitch factor ($f_w \leq 1$). The primary ampere-turns are generally situated in the stator, or outer member, and fulfil two functions: to provide the magnetizing ampere-turns for

the path outside the solid iron and to balance the secondary ampere-turns represented by the resultant of all induced currents. Call the amplitude of the latter component $AT_{pole\ sec}$, and let us establish the connection between these radially magnetizing AT and the tangentially magnetizing $\hat{N}$ in amp/cm of the preceding

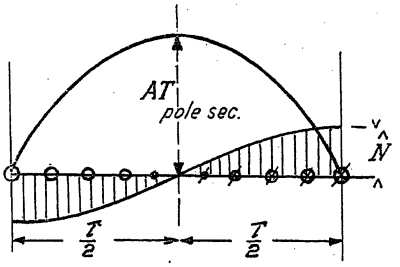


Fig. 13

equations. Fig. 13 shows that $AT_{pole\ sec}$ is the integral of the amp/cm over half a pole arc, i.e. $AT_{pole\ sec} = \hat{N}(2/\pi)(\tau/2)$

whence $$N = 1{\cdot}11\frac{2AT_{pole\ sec}}{\tau} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

N must also be simply related to the familiar A_s, the "specific electric loading," "specific amps" or ampere-conductors per cm. For a 3-phase stator winding, $A_s = 6IT/\tau$ which may be written $1{\cdot}11 \times 2AT_{pole}/f_w\tau$. We can therefore transform equation (16) to

$$N = A_s f_w AT_{pole\ sec}/AT_{pole} \quad . \quad . \quad . \quad . \quad (17)$$

This shows $\hat{N}$, except for the winding factor, to be identical with the specific electric loading referred to the rotor.

If an m.m.f. characterized by Fig. 13 revolves with constant amplitude and speed round the rotor, every square centimetre of the surface experiences the loss l_{e+h} which is ascertainable as shown. The power exerted by the surface forces moving with slip speed $d\pi f_s/p$ relative to the rotor equals this loss. Therefore, expressing the force F_{pole} acting on one pole in dynes, we obtain in watts $2pF_{pole}\frac{d\pi f_s}{p}10^{-7} = l_{e+h}d\pi l$

Whence $$F_{pole} = \frac{l_{e+h}}{2f_s}l10^7 \text{ dynes} = 5{\cdot}1\frac{l_{e+h}}{f_s}l \text{ kg} \quad . \quad . \quad (18)$$

This, at first sight, seems a startling result, because it indicates that the force per pole is independent of the pole arc. The explanation is simple: for a given N the tangential flux, Φ per cm axial length [equation (10a)], is independent of τ, therefore also the radial flux per pole Φ_{pole}, which is $2\Phi l$. The radial induction whose reaction on the induced current created the tangential force F_{pole} is thus inversely proportional to τ, so that this term drops out of the integral of current into induction over τ. From this the torque produced by a rotor of given dimensions is obtained, and its power at a given speed is found to be proportional to the number of poles, always assuming that the electric load is maintained. Another conclusion is that for solid-rotor induction motors with given p and f and a limited N, it pays to design the machine with the smallest possible diameter, since the tangential force per cm axial length is independent of the diameter and the torque is therefore not proportional to d^2, as in all other types of machines, but only to d. Again, in applications such as induction clutches, where p may be chosen freely, it is advantageous to operate with the highest number of poles which heating considerations and the maintenance of a suitable ratio of gap to pole arc will permit.

(2.1.1) *B* **remains Below the Knee of the Magnetization Curve.**

If the synchronous speed and the running speed in revolutions per sec are $n_{syn} = \frac{f}{p}$ and $n = \frac{f}{p}(1-s)$ respectively, and l_{e+h} is taken from equation (15) and $m_s = \sqrt{\frac{\pi f_s c}{\rho}}10^{-8}$, equation (18) will give the following expressions in M.K.S. units:

$$\text{Torque} = 5{\cdot}1\frac{\rho m_s N^2 h}{f_s}lpd\,10^{-2}\text{ kg} = 5{\cdot}1\sqrt{\frac{\pi c\rho}{f_s}}lpdN^2h\,10^{-6}\text{ kg} \quad . \quad . \quad (19)$$

$$\text{Power} = \text{Torque} \times 2\pi\frac{f(1-s)}{p} = 3{\cdot}14\sqrt{\pi c\rho f_s}ldN^2h\frac{1-s}{s}10^{-7}\text{ kW} \quad . \quad (20)$$

This power equation may be checked against the general formula for the induced power P_i of electrical machines based on their dimensions, the mean magnetic loading B_m and the electric loading A_s of the rotor. This formula is

for d.c. machines: $P_i = \pi^2 A_s B_m d^2 ln 10^{-11}$ kW,

and for a.c. machines: $P_i = 1{\cdot}11 f_w \pi^2 A_s B_m d^2 ln 10^{-11}$ kVA

B_m may be replaced by

$$\frac{\Phi_{pole}}{\frac{d\pi l}{2p}} \text{ and since } \Phi_{pole} = \frac{2c}{m_s}Nl,\ B_m = \frac{4}{\pi}\frac{p}{d}\frac{c}{m_s}N,$$

and using equation (17) we get

$$P_i = 4{\cdot}44\sqrt{\pi c\rho f_s}ldN^2\left(\frac{1-s}{s}\right)10^{-7}\text{ kVA}$$

which agrees with equation (20), since

$$\text{kW/kVA} = 0{\cdot}707h = 3{\cdot}14h/4{\cdot}44$$

Equation (20) confirms that for fixed values of N, n, p and s, and therefore $f_s = nps$, the power is proportional to d, not d^2. For given dimensions of d and l of the rotor and of N, n, and s, since the frequency and thus p can be freely chosen, the power is proportional to $\sqrt{f_s}$ and therefore to $\sqrt{p}$. In practice, however, it is generally not the induced N in the secondary part, but the primary electric loading, which is the limiting factor in the design. These practical considerations, especially the conditions resulting from a limited primary m.m.f., will be referred to again later.

(2.1.2) *B* **passes the Knee of the Magnetization Curve.**

For the solid iron and the slip frequency in question the spiral diagram has given the curves of Φ, l_{e+h} and $\cos\psi$ as functions of $\hat{N}$. We have now only to use equation (18) to determine the torque and the power for any value of N. For any Φ, the AT_m to cover the reluctance exterior to the solid iron may then be calculated; from this the primary current and its phase angle can be obtained using the vector diagram Fig. 1.

(2.1.3) **Real and Apparent Resistivity. Means of Raising the Latter.**

The value of ρ to be used in the above equations and, in principle, for the spiral diagram, should cover not only the resistance to the currents along their axial paths of length l, the seat of their e.m.f., but also that of the circumferential paths at the ends, which close the electric circuits and could not be introduced into the fundamental equations. An apparent resistivity ρ_a, instead of the true one ρ, must therefore be introduced. The ratio ρ_a/ρ is a function of l/τ. It is not difficult to find this ratio with sufficient accuracy. In most cases l/τ is large enough to make the ratio ρ_a/ρ = mean total length of current path/axial length of current path sufficiently accurate for practical purposes. The current paths at the ends of the rotor can be estimated more accurately from the streamline principle of least resistance.

We found that, for certain applications, a quality of iron possessing a high value of ρc is desirable. Such alloys are difficult to procure, however, and not easy to machine. It is cheaper and gives more flexibility to use ordinary mild steel with high c, and low ρ, and introduce devices to obtain a higher ratio of ρ_a/ρ. This may be done by making shallow grooves in the active iron at right angles to the direction of the currents, i.e. peripherally in the case of cylindrical surfaces, so as to lengthen the current path. The number and shape of the grooves allows ρ_a to be adjusted to almost any desired value; the effect can be calculated since the depth of penetration into the iron is the same for the current paths round the grooves and along the cylindrical surface.

Grooves are suggested to increase the loss and the torque, and it may be objected that they are also used for just the opposite purpose of reducing eddy-current losses, as in the solid rotors of turbo-alternators. This apparent contradiction is removed if the effect of an increased apparent resistivity on the flux, and hence on the magnetizing component AT_m of the primary current, is considered. If this component is large in proportion to the air-gap between stator and rotor, these grooves might well reduce the loss caused by the secondary current falling very appreciably. For the applications considered here, it is assumed that the air-gap, and therefore the magnetizing component, AT_m, is small. Under these conditions, grooving will have the desired effect of increasing the loss.

(2.2) The Torque of Self-Starting Synchronous Motors with Solid Salient Poles. Means of Improvement

With salient poles in place of a continuous cylindrical iron surface, the starting torque is not only reduced but will fluctuate between a maximum and a minimum according as N is over the centre of a pole, positive or negative, or over the centre of a neutral zone. The frequency of this oscillation will be twice the slip frequency. With a constant c and sinusoidal m.m.f. distribution, the torque will be proportional to $\int \sin^2 \alpha d\alpha$, where α is the electrical angle measured from the centre of a neutral zone. The torque maxima and minima for a ratio of pole arc to pole pitch of 2/3 will therefore correspond to $\int_{\pi/6}^{5\pi/6} \sin^2 \alpha d\alpha = 1{\cdot}48$ and $\int_{-\pi/3}^{+\pi/3} \sin^2 \alpha d\alpha = 0{\cdot}612$ respectively, as against $\int_0^{\pi} \sin^2 \alpha d\alpha = 1{\cdot}57$ for a continuous cylindrical surface. The average torque is thus reduced to 2/3, while the maximum is 0·94 and the minimum 0·39 of those values calculated by equation (10*a*).

For values of B above the knee the average reduction is the same, but the range of torque variation is smaller. The starting performance will therefore be much improved if a surface layer is provided with the optimum magnetic and electric properties, not only to cover the poles but largely, or completely, to bridge the neutral zones. In view of the very small depth of penetration, a bridging sheet of this type can be made thin enough to avoid excessive leakance, and the continuous rotor surface thus obtained will also permit the use of pole-changing windings for a further improvement of the starting performance for special applications.

(2.3) General Considerations on the Influence of Various Factors on the Torque

In motors for a given speed and frequency the electric and magnetic properties of the rotor surface can be altered within wide limits, either by the choice of steel or by grooving. In induction clutches and eddy-current brakes, moreover, there is a free choice of p and hence of f for a given speed. It has already been indicated that the choice of these values is influenced by the part played by the magnetizing component AT_m in determining AT_s, and therefore N, for a given AT_p.

A distinction must be drawn between applications for normal frequencies and those for high frequency. In normal-frequency motors, starting is generally effected by applying a voltage reduced by an auto-transformer to the stator, so as to keep the stator current at a permissible value. As the slip frequency when the motor is stationary has the full value f of the supply system, Φ_{pole} and Φ are similarly reduced, and AT_m is not therefore as important as AT_s. The latter component and N may hence be regarded as almost fixed for a machine of given dimensions. It is seen from equation (19) that the flux, and therefore the starting torque, increase with $\sqrt{\rho_a c}$. This general rule will continue to apply when the induction passes beyond the knee of the characteristic, as Rosenberg has already pointed out. The starting performance can thus be much improved by using for the rotor a steel of high ρc, such as Stalloy, or by applying a thin surface layer of similar material, or by grooving so as to increase ρ_a. The corresponding increase of Φ_{pole} necessitates a higher tapping on the auto-transformer. That a pole-changing winding on the stator for doubling p at starting will be very effective for raising the starting torque is also evident from equation (19), which shows the torque to be proportional to p, other conditions being equal.

A very different situation may arise in such machines as induction clutches and inductor-type eddy-current brakes where a much higher frequency is employed. Because of the large number of poles of very short pitch τ and the fact that for mechanical reasons the air-gap ∂ cannot be reduced below a certain value, ∂/τ is large. AT_m may then become of decisive importance in the diagram shown in Fig. 1. As already indicated, measures taken to increase the flux can then reduce the loss and the torque, because the resulting increase of AT_m for given AT_p may reduce AT_s and N more than Φ is raised. The product $\rho_a c$ will thus have a definite optimum, which may be found by repeated application of equation (19) and Fig. 1. As the optimum is sure to be very flat, it may be closely approached analytically by using the expressions for B below the knee of the characteristic and taking $\psi = 30°$.

Similarly, for given or assumed dimensions, AT_p and n, and also known values of ρ_a and c, the most suitable number of poles can be determined. This optimum, however, will generally be found to lie beyond the practical limits set by the ratio ∂/τ.

(3) ACKNOWLEDGMENT

The author wishes to acknowledge the assistance received from Mr. D. Edmundson of the British Thomson-Houston Co., Ltd., Rugby, who carried out the tests described.

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(5) APPENDICES

(5.1) Flux and Current Distribution in Solid Iron for Constant Permeability, ignoring Hysteresis

Denote the instantaneous values of amp/cm circumference by n_x, current density by g_x and induction in the iron by b_x, all at a depth x below the surface. The r.m.s. values of the electrical quantities are N_x and G_x, and the amplitudes $\hat{N}_x$ and $\hat{G}_x$. Of the magnetic quantities, no r.m.s. values are used. In accordance with custom the capital letter B_x denotes the amplitude. The resultant of all lines of force at depths greater than x is ϕ_x and its amplitude Φ_x. At the surface, $x = 0$, all terms are applied without index.

Let the impressed amp/cm along the surface be $n = \hat{N}\cos\omega t$, where $\omega = 2\pi f$. It is known that the sum of all induced currents, from $x = 0$ to $x = \infty$, is at any instant equal and opposite to n, or $-\hat{N}\cos\omega t$. At the depth x, the sum of the external amp/cm and of all secondary currents down to the depth x, is $n_x = N_x\cos(\omega t + \psi_x)$, where ψ_x is an angle as yet unknown; this sum must be equal and opposite to the sum of all currents in depths greater than x, as shown in Section 1.1.

Therefore $$n_x = -\int_x^\infty g_x dx$$

whence, ignoring hysteresis,

$$b_x = cn_x = -c\int_x^\infty g_x dx$$

where c is the ratio $B/\hat{N}$ from the straight part of the magnetization curve, $g_x = \frac{e_x}{\rho} = -\frac{10^{-8}}{\rho}\int_x^\infty \frac{\partial b_x}{\partial t}dx$, e_x being the e.m.f. per cm induced at the depth x and ρ the resistivity in ohms per cm cube. This last equation assumes that e_x is completely absorbed as ohmic drop where it is induced. When applied to a solid rotor this means that the resistances in the circumferential current paths at the rotor ends are considered negligible compared with the resistance in the axial paths where the induction takes place.

Now $$b_x = \frac{c\,10^{-8}}{\rho}\int_x^\infty\int_x^\infty \frac{\partial b_x}{\partial t}dxdx$$

which twice differentiated gives

$$\frac{\partial^2 b_x}{\partial x^2} = \frac{c\,10^{-8}}{\rho}\frac{\partial b_x}{\partial t}$$

and because $b_x = cn_x$

$$\frac{\partial^2 n_x}{\partial x^2} = \frac{c\,10^{-8}}{\rho}\frac{\partial n_x}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

J. J. Thomson's[2] treatment begins with this equation.

Express $\frac{\partial n_x}{\partial t}$ by a function of n_x not containing t explicitly as a variable, so as to transform equation (1) into an ordinary homogeneous differential equation with constant coefficients. As n_x is a sinusoidal function of t, we may write $n_x = \hat{N}_x\epsilon^{j\omega t} = \hat{N}_x(\cos\omega t + j\sin\omega t)$ where $j = \sqrt{-1}$, keeping in mind that only the real part of n_x applies. This gives $\frac{\partial n_x}{\partial t} = j\omega\hat{N}_x\epsilon^{j\omega t} = j\omega n_x$, which substituted in equation (1) gives $\frac{\partial^2 n_x}{\partial x^2} = \frac{c\,10^{-8}}{\rho}j\omega n_x$ and $\frac{\partial^2 \hat{N}_x}{\partial x^2} = \frac{c\,10^{-8}}{\rho}j\omega\hat{N}_x$, or since $(1+j)^2 = 2j$

$$\frac{\partial^2 \hat{N}_x}{\partial x^2} = m^2(1+j)^2\hat{N}_x \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $$m = \sqrt{\frac{\omega c 10^{-8}}{2\rho}} = \sqrt{\frac{\pi f c}{\rho}10^{-8}} \quad . \quad . \quad . \quad . \quad (3)$$

The well-known general solution of equation (2) is

$$\hat{N}_x = A\epsilon^{m(1+j)x} + B\epsilon^{-m(1+j)x}$$

Of the two integration constants A and B, A is 0, because for $x = \infty$, $\hat{N}_x$ is 0. The instantaneous value is hence given by

$$n_x = \hat{N}_x\epsilon^{j\omega t} = B\epsilon^{-m(1+j)x+j\omega t} = B\epsilon^{-mx}\epsilon^{j(\omega t - mx)}$$
$$= B\epsilon^{-mx}[\cos(\omega t - mx) + j\sin(\omega t - mx)]$$

the sum of two components of which only the real one applies with $B = \hat{N}$ satisfying the boundary conditions for $x = 0$ and $x = \infty$, i.e. $n = \hat{N}\cos\omega t$ and $n = 0$ respectively. We thus arrive at the solution

$$n_x = \hat{N}e^{-mx}\cos(\omega t - mx) \quad . \quad . \quad . \quad . \quad (4)$$
$$b_x = Be^{-mx}\cos(\omega t - mx) \quad . \quad . \quad . \quad . \quad (5)$$

These lead easily to the equations for the current density in the iron, the eddy-current loss, the total flux Φ and the angle ψ as given in Section 1.2.1.

(5.2) The Influence of Hysteresis on the Flux and Current Distribution in Solid Iron for Constant Permeability.

With the same symbols as in Section 5.1, express the hysteresis loss per cm cube of iron by: $L_h = \eta f B^2$, where η is chosen as in Section 1.2.1. This expression, for constant $c = B/\hat{N}$, implies a constant hysteresis angle σ defined by $\sin\sigma = \frac{\eta c}{\pi}10^8$. The amp/cm at the level x below the surface is, as before, given by the real part of $n_x = \hat{N}_x\epsilon^{j\omega t}$, but we have now to write

$$b_x = B_x\epsilon^{j(\omega t - \sigma)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The equation for the current density

$$g_x = \frac{\partial n_x}{\partial x} = \frac{e_x}{\rho} = -\frac{10^{-8}}{\rho}\int_x^\infty \frac{\partial b_x}{\partial t}dx$$

now gives

$$\frac{\partial^2 n_x}{\partial x^2} = \frac{10^{-8}}{\rho}\frac{\partial b_x}{\partial t} = \frac{c}{\rho}10^{-8}\hat{N}_x j\omega\epsilon^{j(\omega t-\sigma)}$$

and because $\frac{\partial^2 n_x}{\partial x^2} = \frac{\partial^2 \hat{N}_x}{\partial x^2}\epsilon^{j\omega t}$

$$\frac{\partial^2 \hat{N}_x}{\partial x^2} = \frac{c}{\rho}10^{-8}\hat{N}_x j\omega\epsilon^{-j\sigma} = \frac{\omega c}{2\rho}10^{-8}(1+j)^2\hat{N}_x\epsilon^{-j\sigma}$$
$$= m^2(1+j)^2\epsilon^{-j\sigma}\hat{N}_x \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where, as before, $$m = \sqrt{\frac{\pi f c}{\rho}10^{-8}}$$

The solution of equation (7) is

$$\hat{N}_x = A\epsilon^{m(1+j)\sqrt{\epsilon^{-j\sigma}}x} + B\epsilon^{-m(1+j)\sqrt{\epsilon^{-j\sigma}}x}$$

with $A = 0$ as $\hat{N}_x = 0$ for $x = \infty$

and $B = \hat{N}$ as $\hat{N}_x = \hat{N}$ for $x = 0$

whence $$n_x = \hat{N}_x\epsilon^{j\omega t} = \hat{N}\epsilon^{-m(1+j)\epsilon^{-j\frac{\sigma}{2}}x + j\omega t}$$

of which only the real part applies.

By introducing $\epsilon^{-j\frac{\sigma}{2}} = \cos\frac{\sigma}{2} - j\sin\frac{\sigma}{2}$, also $\cos\frac{\sigma}{2} + \sin\frac{\sigma}{2} = \sqrt{1+\sin\sigma}$ and $\cos\frac{\sigma}{2} - \sin\frac{\sigma}{2} = \sqrt{1-\sin\sigma}$, the real part is easily found to be

$$n_x = \hat{N}\epsilon^{-\sqrt{1+\sin\sigma}\,mx}\cos\left[\omega t - (\sqrt{1-\sin\sigma})\,mx\right] \quad (8)$$

from which follows

$$b_x = B\epsilon^{-\sqrt{1+\sin\sigma}\,mx}\cos\left[\omega t - (\sqrt{1-\sin\sigma})mx - \sigma\right] \quad (9)$$

Further,

$$g_x = \frac{\partial n_x}{\partial x} = -m\hat{N}e^{-\sqrt{1+\sin\sigma}\,mx}$$
$$\left[\sqrt{1+\sin\sigma}\cos(\omega t - \sqrt{1-\sin\sigma}\,mx) - \sqrt{1-\sin\sigma}\sin(\omega t - \sqrt{1-\sin\sigma}\,mx)\right]$$

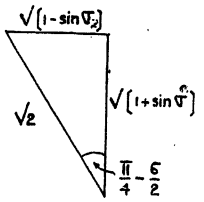


Fig. 14

the sum of two 90° displaced waves, which from Fig. 14 and putting $\sqrt{1+\sin\sigma} = h$, may be written

$$g_x = -\sqrt{2}m\hat{N}\epsilon^{-hmx}\cos\left[\omega t - (\sqrt{1-\sin\sigma})mx + \frac{\pi}{4} - \frac{\sigma}{2}\right] \quad (10)$$

since $\arctan\frac{\sqrt{1-\sin\sigma}}{\sqrt{1+\sin\sigma}} = \frac{\pi}{4} - \frac{\sigma}{2}$

"THE SUPPLY AND DISTRIBUTION SECTIONS OF THE REPORT* ON ELECTRICITY SUPPLY, DISTRIBUTION AND INSTALLATION"

TRANSMISSION SECTION DISCUSSION MEETING, 28TH MARCH, 1944

Mr. P. E. Rycroft, who opened the discussion, remarked that during the last few years post-war planning had become almost an obsession, but that there were very few industries in which planning had been more systematic and scientific than in the electrical industry. The chief difference between pre-war planning and present-day efforts was that in the past they consisted very largely of individual endeavours not formally correlated, whereas now the trend was towards mass planning. It would be quite wrong to allow the general public to think that the electrical industry was in such a chronic state of mismanagement that very large-scale reorganization was necessary. On the contrary, those engaged in the industry could point with pride to the remarkable results achieved by their efforts.

Turning to the Report, Mr. Rycroft pointed out that No. 3 Sub-Committee had devoted eight pages to advocating the standardization of the voltage of consumers' supplies. Some of this space might have been more usefully employed in indicating how it was proposed to provide the money to carry into effect what had been recognized as an essential step many years ago. The chief point of this Section of the Report was that the cost of effecting the necessary changes would be about £17 500 000, which would entail £1 250 000 per annum for the repayment of interest and principal. With an annual income for the whole industry of about £100 000 000, the industry should not find it difficult itself to provide the money for the 20 years probably necessary to liquidate the capital sum. This meant, of course, that the consumer in his turn would have to find the money. At the same time the suggested £17 500 000 could apparently be materially reduced, because it included altering those systems which at present were very near to the required standard. Where there was a difference of only 10 or 20 volts, undertakers should receive legislative authority to give six or twelve months' notice to consumers of the proposed change, thus giving them time to replace their lamps and apparatus, and relieving the undertaking of the cost. The undertaking should not be compelled to give new lamps and small pieces of apparatus in exchange for others that were often almost worn out.

With regard to "Availability of Supply" the Report gave him the impression that there were many consumers, particularly in rural areas, clamouring for electricity they could not get; in his view there was very little evidence of this. The rural area with which he was familiar, an area of 250 sq miles, had 70 villages with a population of 40 000 and some 10 500 houses. No fewer than 7 800 of these premises had already been connected in 13 years, and the total capital expenditure for all purposes, including services, was £250 000, without any subsidies. The present revenue was £63 500 per annum, or a little over 25 per cent of the capital invested. By the system of finance adopted, practically half of the original capital had been repaid, and it was estimated that with a post-war expenditure of a further £90 000 all the properties within the area to which the supply was not at present available, would be served. The total kWh supplied were 8½ millions per annum, of which about 2 million were supplied through prepayment meters. The two-part tariff was on the basis of 15 per cent of the rateable value, with a running charge of ¾d. per kWh. He had a strong preference for the rateable-value basis as against the floor-area basis for the assessment of the fixed charge. The maximum flat rate was 5½d. per kWh and in both cases there was a war surcharge of 20 per cent.

As regards wayleaves he had personally encountered few difficulties, but he regretted that the Committee had not made some suggestions for standardized charges for wayleaves.

In another part of the Report, it was implied that overhead lines were an essential and permanent feature of rural supply. He did not accept this and urged that in many cases underground distribution offered real advantages, judged on a long-term view. In the area he had mentioned, there were 119 miles of low-voltage distribution network with only 35 miles of low-voltage overhead lines.

The value of mechanized farms to the building-up of a load on the electricity undertaking was, he thought, very largely illusory and, in support, he quoted figures of the small consumption of units for the horse power installed in the area already referred to. The value to the undertaking of the farm load actually lay in the increasing use which the farmer's wife made of electric cooking, water heating, etc.

He was doubtful of the suggestion in the Report that services should be supplied free of charge to a limit of cost not greater than was involved in the urban case, and he thought the suggestion of under-eave construction highly controversial and certain

* Prepared by Sub-Committee No. 3 of the Post-War Planning Committee (*Journal I.E.E.*, 1944, 91, Part I, p. 104).

to meet with strenuous opposition from individualist householders.

Finally, he thought that the recommendations in the Report were presumably for the guidance of Government Departments, but he did not consider them emphatic enough. Indeed, he thought the whole matter had been approached with some timidity, and he was emphatic that subsidies of any kind were not an essential feature of successful schemes of rural development.

Among the contributors to the discussion were the Chairman of the Post-War Planning Committee—who was also Chairman of Sub-Committee No. 3—and individual members of the specialist Panels set up for the detailed consideration of various aspects of the Report, who took the opportunity to re-state and elucidate the views set out therein. On the other hand, divergent views were not lacking.

On behalf of the Committee, it was made clear that the Report was not drafted to produce provocative proposals with the object of starting discussions in The Institution, but rather to group together a number of matters on which, so far as the Committee could judge, there was fairly wide agreement in the industry, so that the proper authorities could take effective action. The advocacy of completion and of voltage standardization as a National Industrial Plan was emphasized as a major plank in the recommendations made.

In criticism of the Report, it was said that there would be difficulty in convincing owners of 250-volt systems that they would gain by the change, as there would be a loss of some 15 per cent in system capacity for which no compensation was suggested. The view was emphasized that the Committee should have made definite proposals as to how the change-over was to be effected, and it was thought there was not very much wrong with the present powers of undertakers if rightly used.

A further statement from The Institution of a more imaginative and constructive nature than was contained in the Report, was asked for by one speaker in connection with rural electrification, and it was urged there should be some scheme by which the increased value of land due to a supply of electricity becoming available should contribute towards the cost of bringing electricity into the rural areas.

Another speaker considered the figure of £2 18s., given in the Report as the average cost per kW connected for increasing the voltage from below 220 to the proposed standard, as high, and he wondered from which type of undertaking this average had been derived. An example was mentioned in which the cost worked out at £1 2s. per kW connected, a total of about 17 000 kW being involved.

It was suggested that the Report was inconsistent in advocating standardization of voltage, without at the same time dealing with the change-over from d.c. to a.c., which would considerably increase the estimated cost of £17 500 000. Another general point was that voltage standardization, complete or partial—leaving 250 volts as a secondary standard—would be beneficial to manufacturers, undertakers and consumers alike, and it was thought to be not unreasonable to expect lamp makers, motor manufacturers and heating-element makers to assist in this by quoting specially favourable terms for replacing or rewinding non-standard articles. It was recalled that some progress in this direction was made before the war.

In regard to rural supplies, emphasis was laid on the fact that capital costs were often twice those in urban areas, and the Committee was criticized for not taking this sufficiently into account and for making no allowance for depreciation, repairs and maintenance. These charges were said by one speaker, who claimed wide experience, to be just as heavy in rural work as the capital charges. Subsidies for rural development were opposed, if only for the reason that they would mean Treasury control. Attention was called to the lack of statistics with regard to rural electrification, and the concrete figures given by Mr. Rycroft were welcomed. Another example was mentioned of a rural area of 4 300 sq miles containing 220 000 premises, where the supply was said to be available to no less than 80 per cent of the premises, no fewer than 176 000 being connected, including 3 100 farms. Of the latter 600 were completely isolated with no other building within half a mile.

DISCUSSION ON "BOILER-HOUSE MEASUREMENT AND CONTROL FOR EFFICIENT FUEL UTILIZATION"*

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 1ST NOVEMBER, 1943

Mr. T. Coates: I am interested from the power station aspect in the accuracy demanded of meters by users. I do not think that we can be blamed for insisting on test accuracy so far as boilers are concerned, because it is realized that it is unnecessary to ask for an instrument with an exceptional degree of accuracy since very large quantities are being measured and the readings can only be taken from a few points which it is hoped will give a reliable mean value either of draught, furnace temperature or gas analysis. Dependability and not accuracy is therefore insisted on; this factor is by far the more important and should be closely studied by instrument makers in the production of industrial instruments.

Up to quite recently boilers were operated on two gauges—water gauge and pressure gauge. Substantial progress has been made beyond these two gauges and a modern boiler may now have up to 78 instruments. At the same time, efficiency has increased considerably, and to maintain this higher standard it is essential to know the conditions and the changes they are subject to in each different part of the plant. The authors apparently assume that before an instrument is installed, the engineer wants to know what saving will be effected. While this may be so on small plants, on large plants a wider view is taken and it is realized that full details of the performance must be available to forestall any severe maintenance problem liable to impair the efficiency of the plant.

The authors lay stress on CO_2 meters, which were the first type of meter giving an insight into the performance of a boiler. These meters have always been a source of trouble, and the authors admit that they need much attention. It would have been more satisfactory if they had promised a CO_2 meter in the near future which could maintain an accurate reading over a number of years

* Paper by G. H. BARKER and A. L. HANCOCK (see 1943, 90, Part II, p. 217).

The authors measure the air flow for automatic control by the differential pressure across the boiler, presumably from the bottom of the combustion chamber to the gas exit before the air heaters. Surely this is a doubtful quantity and depends to a large extent on the cleanliness of the boiler tubes. Mention is made that in some cases a Venturi tube is fitted in the air ducts to get more accurate results, but where this is impracticable could not sufficient accuracy be obtained by means of Pitot tubes?

The main advantage of automatic control would appear to be that, instead of regulating a boiler on half a dozen controls or more, the attendant has only to deal with one, namely the fuel/air constant. This constant does not hold for all load conditions and it is impossible to take into account variations in the quality of coal. It appears therefore that the attendant has to regulate the fuel/air control just as often as he would the normal controls on a hand-controlled boiler.

It is satisfactory to note that the authors do not claim any fantastic figures for saving in efficiency; yet it is disappointing that they do not indicate what figures can be realized. Mention is made in the paper that even if the saving is only 0·5% it is worth consideration. I agree; in large power stations this figure would represent a saving of £7 000 per year in coal cost alone. The main saving with automatic control appears to be that it is possible to run boilers nearer the maximum pressure. Whereas this does not make much difference to the boiler efficiency it does improve the turbine efficiency and for approximately every 7-lb/in^2 increase in pressure the efficiency is raised by 0·1%. It will be interesting to have some figures showing the difference between plant operating at a constant pressure and plant operating with a 50-lb/in^2 fluctuation.

Mr. V. L. Farthing: Only a year or so ago, it was difficult to get the ordinary industrial engineer interested in a CO_2 recorder: now it is difficult to persuade him to wait patiently for the instrument he has at last ordered.

In 1938, we at the Liverpool Engineering Society, had a paper on automatic control by Mr. J. E. O'Breen, but it was a little before its time. Now the national necessity for fuel economy has brought the subject again to the fore.

Most members of The Institution are probably power-station engineers with very heavy coal bills. A saving of 0·5 per cent is worth considering, and most manufacturers of control equipment will guarantee that percentage. Possibly most members of the Liverpool Engineering Society are more concerned with Lancashire and economic boilers, and with these industrial plants it is quite common to make at least a 3–5% saving.

Mr. E. J. Evans: The measurement aspect of this paper, despite the title, appears to be subordinate to the authors' real subject of automatic boiler control. Does not the former warrant a separate paper?

In many cases the virtues of automatic boiler control are apparent without reference to minor increases in boiler efficiency, which may or may not be attainable. The authors mention several examples of automatic control in power-generation practice—the universal use of automatic voltage control might be added—all of which are fully justified without considering fuel economy. On the other hand, I would ask the authors to extend their reply to a question, in the London discussion, on the value of automatic boiler control in base-load stations. Some industrial-boiler installations are in every way comparable with public-supply base-load plants and are operated at the highest attainable outputs per unit of installed capacity. What advantages would automatic boiler control offer in the case of a large industrial boiler plant, fired with powdered fuel, with full instrumentation and complete remote manual control, operating at high efficiency and an average load of approximately 90% of m.c.r. for about 90% of the maximum possible running hours per annum?

The authors refer to the high degree of reliability inherent in the components employed for automatic boiler control. Would they agree that such reliability cannot be fully obtained without a high standard of maintenance, and that automatic boiler control will not be given unbiased recognition until general instrument maintenance, excluding kWh meters, receives more care and organization than at present in the average generating station?

In the measurements part of the paper, the authors point out in their table of essential instruments, that feed-water meters are necessary for efficiency determinations and that steam meters are required for indications of load, etc. Would the authors agree that water metering as the basis of boiler test codes results from its inherent accuracy being greater when such codes were drawn up than steam metering. Using all due corrections is it not true that modern steam metering can be comparable with water metering, bearing in mind the authors' comments on the accuracy of measurement desirable in boiler operation?

In view of the present fuel difficulties and the desirability of statements on the commerical efficiency of boilers being based on the useful output, i.e. allowing for loss of steam to soot-blowing, has not the time arrived when boiler efficiency should be determined on steam output instead of water input?

Flow measurement is of increasing value, particularly in respect of the authors' subject. The new B.S. Code on flow measurement, dealing with the differential-pressure devices employed, namely nozzles, orifice plates and Venturi tubes, is a most important publication. Would the authors give some information on the general utility of these devices with their associated indicators, recorders and integrators in boiler house measurements?

Mr. J. L. Ashworth: There appears to be a tendency to-day to make instrument mechanism too elaborate. I think instruments for boiler-house work should be of simple, robust construction, and should be provided wherever possible with a means for rapidly checking the instrument. The operating engineer wants an instrument with a high degree of reliability, rather than a high degree of accuracy. Instruments should be designed to require the minimum amount of maintenance.

I am surprised that the authors have not included the critical pressure gauge in their schedule of essential instruments, although they have mentioned it in the paper. This gauge is a valuable and useful equipment in the boiler house and gives immediate indications of any slight change in steam demand.

Automatic boiler control is the logical outcome of increased progress in measurement and control in the boiler house. It performs simple actions required by changes in steam demand, thus freeing the operator for the really skilled work of efficiently burning the fuel on the grates. Automatic control can supply the correct total quantity of air, but cannot admit the air in the correct proportions over the length of the fuel bed. This is the work of the operator, who is guided by his experience with different ranks of coal. The thickness of the fuel bed frequently requires adjusting, which again depends on the rank of the coal. Efficient combustion requires a fixed length of fuel bed. A different quality of coal coming on to the grate can cause a rapid shortening of the fuel bed with the resulting escape of excess air from the back end of the grate.

Without automatic control, the operator's main concern is maintaining steam pressure, efficient combustion becoming a secondary matter. With automatic control, the operator is relieved of the anxiety of attempting to maintain constant steam pressure and can make combustion his main concern.

Mr. D. K. Coldwell: At the beginning of the paper the authors state that the pressure gauge is outmoded, yet later they describe its importance for automatic control.

Air-flow meters should be adopted more generally, as, in collaboration with coal meters, proper combustion can be attained independent of the flow meters. Automatic control will maintain constant pressure, and any saving in fuel can only be made by attention to fires and the coal/air ratio. The installation of automatic control leaves the combustion or stoker personnel more time to attend to this important item.

The instruments should be as reliable as those used on the electrical side.

The modern boiler is being equipped with far too many instruments; one speaker mentioned 78, and in the paper 22 are given, whereas eight to twelve should be quite sufficient.

Mr. J. Goulden: Every boiler should be fitted with sufficient temperature indicators to enable the engineer to satisfy himself that boiler, superheater, economizer and air-heater are all doing their designed duty. I consider temperature recorders are necessary for steam, feed water and final gas, and have found steam-flow/air-flow meters very useful and easily understood by the operators. CO_2 instruments should also be included in the equipment.

We have had automatic control of feed-water, superheat, furnace pressure and soot-blowers. These arrangements have been very successful, and I think fully automatic boiler control will become general in the near future. In my view, the main thing about automatic control is that it relieves the operator of much tedious work and enables him to devote his attention to other essential, but often neglected, duties, the most important being the control of firing conditions in regard to thickness of fuel bed, air distribution and burn off. I think 0·5% has been mentioned as a likely improvement in efficiency from the application of fully-automatic control to a modern boiler plant. Whilst agreeing with this, I think it would be very difficult indeed to prove such a small gain.

Mr. S. R. Hollway: The authors do not state what happens in a power station where there are a number of changes of coal during the day; has the automatic regulator to be re-set for each change?

In Section 6 the authors describe a boiler efficiency meter. Taking the particular case of a stoker-fired boiler, the use of items 1, 2 and 3 for determining the top line of the efficiency equation is apparently sound, but items 4 and 5 are open to question. Normally, when fuels are of reasonable quality the meter may give a close approximation to the true efficiency. One of the present-day difficulties, however, is that combustion is not completed in the length of the stoker and a considerable loss takes place due to unconsumed fuel in the ash. An instrument designed on the lines suggested would take no account of such loss, as the authors infer, and since low-grade fuels are likely to remain in use for some years after the war this type of meter would appear to be ruled out for a long time to come.

The authors state that with automatic control the operator is relieved of the "most exacting part of the control problem, and has more time to devote to those matters over which the automatic control system *can have no influence*, e.g. fuel-bed conditions." Surely the very factors that we automatically control are those which ultimately determine the fuel-bed condition? The provision of an overriding control in the hands of the manual operator is a confession of partial failure on the part of the automatic system. If the operator is in the habit of carrying an excessive draught under hand-control conditions, a very common failing, the same operator will use the overriding control to carry an excessive air-flow/fuel-flow ratio with automatic control.

Mr. W. L. M. French: There has been much controversy in the past in connection with automatic boiler control, as to whether the master controller should be governed by the steam pressure or by the steam flow. The paper lays particular emphasis on regulation by steam pressure. Would the authors explain the reason for this?

After lengthy experience with the steam-flow/air-flow apparatus used in conjunction with automatic boiler control, I have come to the conclusion that it is very reliable. It is, in my opinion, superior to any form of CO_2 instrument in the attainment of combustion efficiency, whether used for automatic or manual control.

The authors have not referred in any great length to the automatic control of pulverized-fuel boilers, although, I believe, automatic control of large power-station boilers has been developed very largely with this form of firing. It appears that automatic control is much more complete where pulverized-fuel firing is adopted, because there is not the need for the operators to take care of the troublesome fuel-bed conditions of stoker-fired boilers.

Mr. E. H. Jones: Of the number of instruments recommended for use in connection with the modern boiler, nine are recorders. In a battery of 10 or 15 boilers, the time taken merely to change the charts, ink the pens and wind the clocks will take up most of a morning. It is possible to have too many recording instruments with the result that, after a lapse of time, the charts are not changed at all.

The authors are prone to fix all the blame for inefficiency on the boiler attendant who is actually operating the boiler. This is hardly fair. Inefficient operation can be broadly divided into two classes: (*a*) where an improvement may be obtained immediately, by operating the boiler controls, and (*b*) those instances which arise from fouled heating surfaces or some mechanical defect, and can only be rectified by taking the unit off the line. Automatic control would be of no help in (*b*), but may prove valuable in prolonging the period of normal running before such conditions arise.

It is important to realize that a boiler furnace has not merely to be adjusted—it has to be managed. So far as adjustments go the automatic controller will always be better than a human being. For this reason, feed-water flow, furnace pressure, and steam-temperature control are best handled automatically. The first is already universal and the other two are obvious developments, but the authors' statement that adopting these three measures leaves only a "short step" to the adoption of fully-automatic control, cannot be accepted. The controller may be very unsatisfactory on the *management* of a furnace—as the authors admit. This calls for a combustion engineer or a highly-trained stoker with the ability to think ahead.

The authors stress the accuracy with which automatic control follows changes in the loading of the plant, and the assumption seems to be that the closer the variations are followed, the more efficient will be the operation. It would be interesting to have their view on a special case—that of a base-load power station. The supposed advantages of base-load working are steady conditions which lead to more efficient operation. There is now a tendency to fit very sensitive speed governors to large modern turbo-alternators, owing to anxiety about the conditions which may arise when those machines throw off a large electrical load and overspeed. These governors have such a "flat" characteristic that they are sensitive to minor changes in the supply frequency such as continually occur throughout the day. It is not uncommon for the output of a base-load station to vary by as much as 15% in as many minutes, simply as a result of the automatic response of the governors to a relatively small change in the supply-system frequency. Do the authors con-

sider that variations such as this should be faithfully followed by the boiler-house automatic control? Would it not be better to devise some means of an automatic nature to eliminate these undesired fluctuations and restore to the base-load stations the advantages of a truly steady load?

Mr. F. J. Worland: In Section 4, the authors state that the purpose of maintaining a slight negative pressure in the combustion chamber, "is concerned with the time required for combustion, the development of the desirable degree of turbulence, and the prevention of uncontrolled air admission, or, of leakage from the furnace." The second two reasons are obvious, but hardly the first two. Would the authors give further information of the relationship between slight negative furnace pressure and the time and turbulence requisites of combustion?

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. G. H. Barker and **A. L. Hancock** (*in reply*): Much has been said about the accuracy and dependability of boiler instruments. In seeking perfection, several points must always be borne in mind, namely (1) that as the value of a measuring instrument rests upon the use made of its readings, the closest co-operation is required between maker and user; (2) an increase in accuracy, i.e. sensitivity, must usually be paid for by reduced resistance to adverse conditions of use; therefore, the accuracy demanded should not exceed that required for the proper conduct of the process; (3) comparisons must be of similar instruments undertaking the same measurement; and (4) in judging performance, the nature of the measurement being made must be understood, e.g. many complaints against the CO_2 recorder are misdirected.

Mr. French compares the steam-flow/air-flow meter and the CO_2 recorder, to the great advantage of the former. On the score of reliability the meter gains, because its duty is so very much simpler. There cannot be any other comparison, for the two instruments make quite different, although related, measurements and are mutually dependent.

Mr. Coates asks whether air flow through the boiler could not be better measured with a Pitot tube. The objections are: (*a*) its extreme susceptibility to choking, and (*b*) the arbitrary differential pressure it produces.

We agree with Mr. Evans. There is little to choose between the accuracies of corrected steam-flow meters and feed-water meters corrected for temperature. The choice will depend upon the plant and its economics, but on large, complex plants both measurements are essential for good control.

Further to the comments of Mr. Ashworth and Mr. Goulden, we might add that the automatic-control system must be judged on what it sets out to do, and not by what one would like it to be able to do. As indicated in the paper the duties of the modern automatic boiler-control system are quite clearly defined. The choice of 0·5% as the minimum gain in efficiency to be expected was deliberate. As anticipated, speakers with practical experience of automatic control quote much greater savings.

On the question of furnace management, it must be clear that the automatic control system cannot take any part in this beyond its variation of the fuel-input rate. Furnace management commences with the design of the furnace and the selection of the fuel; so many of the dependent operating factors are matters of chance and not matters of law, that furnace management must always remain a man-function.

Mr. Coates suggests that under automatic control the boiler attendant would have to regulate the single fuel-air control as frequently as he operates the several controllers under manual operation. The fuel/air ratio to be imposed initially under automatic control will be the best average for the known conditions. Any error will be of fractional magnitude and very much less than the normal errors of the best manual operation. Under manual control, a fluctuation of, say, 1% about a mean of 14% CO_2 means a variation in the excess air percentage of from 22 to very nearly 40 per cent. With automatic control, the pre-imposed fuel/air ratio is maintained consistently, and the errors resulting from load-change and calorific-value variations will only be small. The ratio can be altered precisely at any time by a simple, readily accessible adjustment. This means of adjustment can be locked, which disposes of the point raised by Mr. Hollway.

It is usually argued that in the base-load station a gain in efficiency through automatic control is most unlikely, as there is no steam-pressure problem because of the constant load. But pressure records of central power stations show that the variation mentioned by Mr. Coates, i.e. 50 lb about a mean of, say, 625 lb/in.^{2} is common.

Mr. Jones may be interested to note that the steam-pressure variation to which the automatic-control system shall respond may be determined by the operating engineer. He can adjust its sensitivity to pressure changes to suit his own requirements.

In answer to Mr. Worland, the first point is that of the velocity condition within the combustion chamber from the point of view of combustion efficiency. The choice of pressure is determined by the reasons given. Pressure change is chosen as the basis for automatic control as steam pressure is the only reliable index of the balance between heat input and output. Consequently, it is the only basis for precise control. As the measured pressure change results from a change in the steam-flow rate, they are virtually equivalent.

The purpose of the critical pressure gauge is to induce the fireman to be concerned with relatively small fluctuations about a mean and thus induce a quicker response to the changes in load, so that radical changes in the combustion rate may be avoided.

The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers

THE JOURNAL OF THE INSTITUTION OF ELECTRICAL ENGINEERS

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PROCEEDINGS OF THE SECTIONS OF THE INSTITUTION*

INSTALLATIONS SECTION

23RD MEETING OF THE INSTALLATIONS SECTION, 13TH APRIL, 1944

Mr. A. G. Ramsey, O.B.E., B.Sc.(Eng.), Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 9th March, 1944, were taken as read and were confirmed.

The Chairman announced the nominations to fill the vacancies which would occur on the Committee on the 30th September, 1944.

In the event of a ballot for the new Committee being required, Messrs. A. Morgan and C. W. M. Phillips were appointed scrutineers.

A paper by Mr. C. A. Cameron Brown, B.Sc., Associate Member, entitled "The Electrical Aspect of Farm Mechanization," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

24TH MEETING OF THE INSTALLATIONS SECTION, 4TH MAY, 1944

Mr. A. G. Ramsey, O.B.E., B.Sc.(Eng.), Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 13th April, 1944, were taken as read and were confirmed.

A paper by Messrs. W. N. C. Clinch, Member, and F. Lynn, entitled "The Design and Performance of Domestic Electric Appliances," was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

MEASUREMENTS SECTION

114TH MEETING OF THE MEASUREMENTS SECTION, 21ST APRIL, 1944

Mr. E. W. Moss, Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 31st March, 1944, were taken as read and were confirmed.

The Chairman announced the nominations to fill the vacancies which would occur on the Committee on the 30th September, 1944.

In the event of a ballot for the new Committee being required, Messrs. A. J. Gibbons, B.Sc.Tech., and H. S. Petch, B.Sc.(Eng.), were appointed scrutineers.

A paper by Dr. L. Jacob, M.Sc., entitled "A New Type of Electron-Optical Voltmeter" was read and discussed. The paper was accompanied by a demonstration of apparatus.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

TRANSMISSION SECTION

60TH MEETING OF THE TRANSMISSION SECTION, 12TH APRIL, 1944

Mr. T. R. Scott, D.F.C., B.Sc., Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 28th March, 1944, were taken as read and were confirmed.

The Chairman announced the nominations to fill the vacancies which would occur on the Committee on the 30th September, 1944.

In the event of a ballot for the new Committee being required, Messrs. F. N. Beaumont and A. E. Nicol were appointed scrutineers.

A paper by Messrs. G. W. Preston and H. G. Taylor, D.Sc. (Eng.), Associate Members, entitled "Copper Conductors for Overhead Lines," was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

61ST MEETING OF THE TRANSMISSION SECTION, 10TH MAY, 1944

Mr. T. R. Scott, D.F.C., B.Sc., Chairman of the Section, took the chair at 5.30 p.m.

The minutes of the meeting held on the 12th April, 1944, were taken as read and were confirmed.

A paper by Mr. J. L. Carr, B.Sc., Member, entitled "Remote Switching by Superimposed Currents," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

* Excluding the Wireless Section, the Proceedings of which will be found in Part I and also in Par III of the *Journal*.

STANDARDS OF PERFORMANCE OF GENERATING PLANT, BASED ON FIVE YEARS' OPERATING DATA

By R. W. BILES, Member,* and G. W. MAXFIELD, Associate Member.*

(*The paper was first received* 17*th August, and in revised form* 21*st December*, 1943. *It was read before* THE INSTITUTION 3*rd February, before the* WESTERN CENTRE 14*th February, and before the* SOUTH MIDLAND CENTRE 1*st May*, 1944.)

SUMMARY

The paper is a review of the performance of a group of generating stations over a 5-year period, with comments upon coal qualities, thermal efficiency, analysis of the different classes of breakdown with deductions as to probable operating life between breakdowns, plant availability and the effects of loading.

The plant under review is divided into three groups, pre-1930, 1930–1937 and 1938–1942. From the results, curves for maximum probable availability are deduced.

The suggestion is made that "operating efficiency" should be calculated on a uniform basis and included in station records. The need for an overall standard by which the performance of generating stations can be judged is discussed, and the term "standard merit," based upon operating efficiency and plant availability, is suggested.

(1) INTRODUCTION

Loading conditions on generating plant during the past 5 years, and particularly on the group of generating stations upon which observations are being made, have been considerably above normal.

During the last three years of the period the installation of new generating plant did not keep pace with requirements and in consequence the existing plant was called upon to generate at much higher load factors.

These conditions and difficulties arising therefrom prompted the authors to make a special study of operation records with a view to summarizing the performance of the generating stations separated into the appropriate groups for the purpose. The reasons for the rapid increase in load are of no particular concern in the investigations and have therefore been omitted.

In the Sections which follow data are given regarding actual results from which the suggestions for standards of performance have been made. There would appear to be some good grounds for combining an availability efficiency with an operating efficiency to be called "standard merit" as a measure of a station's performance.

(2) TOTAL PLANT CAPACITY AND OUTPUT

Fig. 1 shows the record of installed plant capacity in each year, available capacity and annual outputs in kWh per kW of available capacity, with a corresponding load-factor scale.

It will be noted that the total installed plant over the period rose from 553·5 to 778·5 MW, an increase of 225 MW. The average available plant capacity rose from 424·5 to 537·8 MW, an increase of 113·3 MW.

It is noticeable that the available capacity in 1940, 1941 and 1942 is almost constant; this is a primary factor which prompted the investigations. The increments in load, however, continued uniformly throughout the period and the annual output per kW of available capacity rose from 4 892 kWh to 6 722 kWh, i.e. the average running plant load factor increased from 56% to 77%.

The figures for the last three years of the period, namely 1940, 1941 and 1942, demonstrate the heavy increase in loading on the available plant capacity.

The turbine plant and boiler sizes are shown in Table 1,

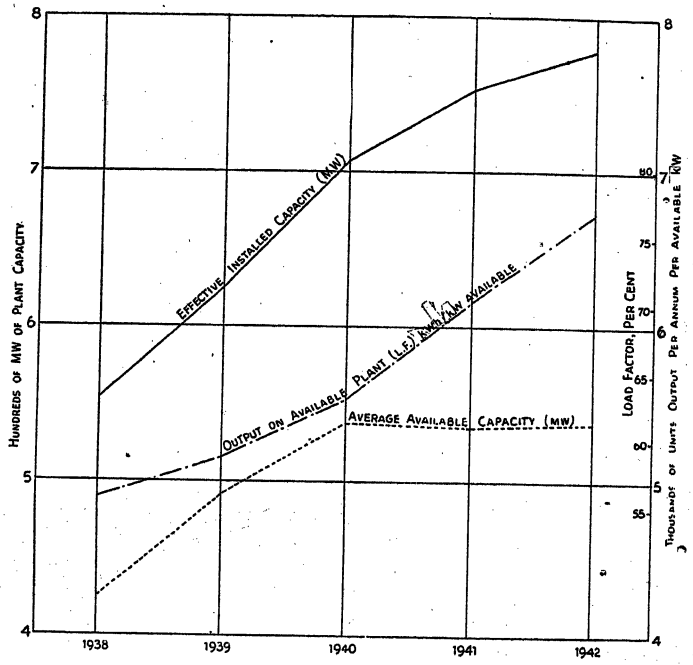


Fig. 1.—Plant capacity and annual average output per available kW.

together with the groups of plant which are being separately reviewed. The turbines number 77 and the boilers 144.

(3) COAL QUALITY AND SUITABILITY

The total coal burnt was mainly from South Wales and Forest of Dean coalfields, with a small percentage from the Midlands and Northumberland. The fuel supplied during the first two years of the period was of superior quality to that supplied during the last three years of the period.

The calorific value of South Wales fuel is usually high and was generally maintained throughout. There was difficulty in obtaining the rated outputs from the boiler plant, as amongst other factors the volatile content, ash content and grading of the fuel varied considerably.

Ash contents were high, owing to unwashed coal being received from the collieries. Coal with a proportion of fines above normal was common; this was due to lack of grading before despatch.

Many of the boilers, particularly of the older design installed before 1930, frequently had to burn coal with low volatile and high carbon contents totally unsuitable for them; particularly where draught was poor, there were numerous occasions when fires could not be kept alight. The high carbon and low volatile content resulted in poor efficiency of combustion, and the percentage of combustible in ash was high. During the last six months of 1942 approximately 136 500 tons of ash was recorded out of 821 000 tons of coal burnt, or 16·6%. Carbon in ash on some stoker-fired boilers was as high as 40%.

* Central Electricity Board.

Table 1

		Turbine plant					Boiler plant				
		Set capacity	Number of sets	Total capacity	Temperature	Average age and size	Boiler capacity	Number of boilers	Total capacity	Temperature	Average age and size
Group A	Pressure 150–275 lb/in² Pre-1930	MW		MW	°F		lb × 10³		lb × 10³	°F	
		1·25	3	3·75	650		20	20	400	538–650	
		1·5	3	4·5	588–660		25	12	300	488–638	
		1·875	2	3·75	650–700		30	10	300	600–700	
		2·5	1	2·5	600		35	27	945	538–750	
		3·0	3	9·0	588–700		40	13	520	585–740	
		3·75	9	33·75	540–700		50	6	300	600–750	
		4·15	1	4·15	532	17 years	55	1	55	650	18 years
		5·0	9	45·0	588–700	5·91 MW	60	4	240	650–700	38 × 10³ lb
		6·0	4	24·0	532–750		65	2	130	650	
		7·0	5	35·0	532–660		70	2	140	538	
		7·5	8	60·0	550–700		80	3	240	570–650	
		10·0	6	60·0	650–750		90	2	180	600	
		12·5	1	12·5	588		100	2	200	730	
		15·0	3	45·0	550–750						
		Total	58	342·9			Total	104	3 950		
Group B	Pressure 300–600 lb/in² 1930–1937	18	1	18·0	725		60	8	480	750	
		20	3	60·0	700–725		80	6	480	800	
		25	3	75·0	725–800	12 years	160	4	640	825	12 years
		30	2	60·0	825	26·3 MW	190	3	570	800	122 × 10³ lb
		50	1	50·0	800		220	4	880	850	
		Total	10	263·0			Total	25	3 050		
Group C	Pressure 300–600 lb/in² 1938–1942	20·0	2	40·0	800		100	2	200	820	
		30·0	5	150·0	825–850		150	4	600	825–875	
		37·5	1	37·5	825	3 years	160	3	480	825	3 years
		50·0	1	50·0	800	30·8 MW	180	4	720	850	164 × 10³ lb
							230	2	460	850	
		Total	9	277·5			Total	15	2 460		
Cooling-tower plant totals—60 MW in Group A only							Powdered-fuel plant totals—Group A. 60 × 10³ lb/hr Group B. 880 × 10³ lb/hr Group C. 1 180 × 10³ lb/hr				
Remainder—Sea or river water							Remainder—Chain-grate stokers				

Fig. 2 shows the average grading and approximate analysis of the fuel supplied in 1939 and 1942 respectively. The increase in fines and ash content is notable in 1942.

Unsuitability of fuel led to an increase in repairs and maintenance, particularly on grates and brickwork. Ash plant also suffered owing to handling greater quantities of ash in an unspent condition.

It seems appropriate to mention that the unsuitable fuels led to a loss of generating capacity estimated to vary between 10% and 15%. Based on the average capacity installed for 1942, i.e. 778·5 MW, the minimum daily loss was nearly 78 MW throughout the year.

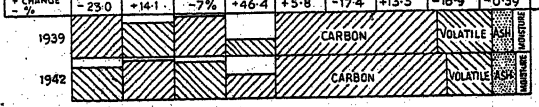
If the full outputs are to be obtained from the older boiler plant still in service, there would seem to be no alternative (except at the great expense of structural alterations to make them suitable for burning low-grade fuels) to supplying them with the correct type and quality of fuel.

(4) THERMAL EFFICIENCY

The weighted average thermal efficiencies have been separated into two groups (Fig. 2). Both groups of plant, operating at pressures from 150 to 275 lb/in² and 300–600 lb/in² respectively, show a general fall over the period, although, as already seen, the actual average running plant load factors have increased and a general rise in thermal efficiency might have been anticipated.

The greater part of the falling-off in thermal efficiency has been

	Grading				Proximate Analysis					
Year	Over ¼" % Mesh	Between ¼" & ⅛" %	Between ⅛" & No 14 B.S.S. %	Through No 14 B.S.S. %	1 Carbon %	2 Volatile %	3 Ash %	4 Moisture %	5 Calorific Value	Total Quantity of Coal
1939	31·7	25·6	30·2	12·5	63·9	21·3	8·3	6·5	13066	1,136,000
1942	24·4	29·2	28·1	18·3	67·6	17·6	9·4	5·4	13015	1,390,223
+ Change − %	−23·0	+14·1	−7%	+46·4	+5·8	−17·4	+13·3	−16·9	−0·39	+22·38



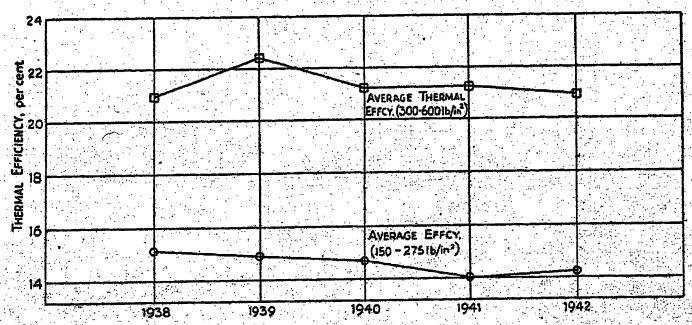


Fig. 2

attributed to the use of inferior coals. The remainder is probably due to the greater use of the older plant, particularly in the lower-pressure group, which, being of higher steam consumption, depressed the combined thermal efficiency.

The maximum probable efficiencies (sent out) to be expected from the stations in the lower-pressure group, assuming they were operated at about 80% running load factor, would be between 16·15% and 21·85% approximately, according to upper and lower limits of operating pressures in the group.

In the higher-pressure group operating between 300 and 600 lb/in², the corresponding figure would be of the order of 21·85% to 26·6%.

The results achieved are believed to be the best that could be obtained with the running load factors and difficult conditions prevailing during the greater part of the period.

(5) ANALYSIS OF BREAKDOWNS

The original records were intended for assessing the gross liability of breakdown, and in preparing Table 2 it has not been possible to separate subsidiary items. They have therefore been classified broadly into sections of plant affected. Space will not permit amplification and it is felt that such detail would not be pertinent to the present investigation, although more studies of individual components would no doubt be welcomed by, and be of benefit to, the electricity supply industry.

Each item has been dealt with by the engineers and manufacturers, and from experience gained the improvements in quality of material and/or design will have been made where possible.

Broadly, the majority of breakdowns were due to mechanical failures from fair wear and tear as distinct from faulty materials or design.

Breakdown periods can be curtailed by ample supply of spare parts, adequate skilled repair staffs, and in particular by arranging for as many items as possible to be dealt with during the annual overhaul or other planned outage. Some incipient defects can be deferred until another item of associated plant needs attention.

In each year of operation a programme of major overhauls is arranged to put the plant into running condition for the next 12 months. If the overhaul is thorough and complete it is probable that many breakdowns will be avoided.

The practice of renewing worn or doubtful parts depends largely upon the judgment of the engineers concerned; some will take a risk whereas others will make a replacement.

In the last three years under review the outage periods allowed for annual overhaul were unavoidably minimized, and the authors consider it probable that in some cases the repairs and overhauls were curtailed as compared with more normal conditions. There was thus a tendency for more breakdowns than usual.

Whilst these special conditions may have been contributory to the excess breakdowns, most of them were no doubt due to higher loading conditions, the effect of which is to bring forward the period for overhaul. If this cannot be done there is a risk of a breakdown, and on some types of plant a half-yearly inspection may be necessary.

During 1942 the total number of breakdowns in all groups amounted to 747, approximately two-thirds of which were due to boilers and boiler auxiliaries, and one-quarter to turbines, each breakdown causing a loss of effective capacity.

Fig. 3 is a day duration curve, and neglecting breakdowns of less than one day duration (when the turbine and boiler breakdowns are almost equally frequent), this Figure shows that boiler plant is the predominating cause of loss of capacity.

The items recorded are the major ones, but many of the plant defects were dealt with by the station operating engineers before a loss of capacity was incurred.

The daily total simultaneous breakdown figure varied from 16·5 MW (minimum) to 167 MW (maximum).

Table 2 is a summary and classification of causes of breakdowns under three groups of plant.

Items 1–7 inclusive concern boiler plant and ancillaries, Items 8–19 turbine plant and ancillaries, and Item 20 miscellaneous unclassified.

The analysis has been examined from two points of view:—

(*a*) The effect of loading.

(*b*) The incidence of breakdowns per unit of plant.

All items would not be equally affected by higher and more continuous loading, and attention is drawn to the following:—

(5.1) Item 2—Boiler Tubes, Drums and Ranges

In plant Group A (150–275 lb/in²) the breakdowns rose from 12 in 1939 to 70 in 1942. With a total of 216 over the 5-year period, and 105 boilers installed on the average during that period, there were 2·06 breakdowns per boiler.

In plant Group B the breakdowns rose from 6 in 1938 to 10 in 1942, with a total of 46 breakdowns for the 5-year period. With an average of 25 boilers installed, there were 1·84 breakdowns per boiler.

In plant Group C the number of breakdowns rose from 2 in 1939 to 17 in 1942, with a total of 35 over the 4-year period. There were 3·5 breakdowns per boiler on an average of 10 boilers (entered as 4·17 for 5 years).

Group C shows the worst performance on the basis of breakdowns per boiler; this may be to some extent due to "teething" troubles in new plant.

(5.2) Item 3—Stokers and Brickwork

By far the greater number of breakdowns on boiler plant fall within this item, which accounts for some 30% of the total.

There is a marked indication of the breakdown liability rising with increased loading in all the groups.

The number of breakdowns per boiler in each group is noticeably similar, and it might have been expected that the newer boilers (as represented in Group C) would have shown a better performance.

(5.3) Item 4—Economizers and Air-heaters

It should be borne in mind that a large proportion of Group A boilers are not equipped with air-heaters, but Groups B and C are so equipped. Unfortunately, the further segregation into economizers and air-heaters separately cannot readily be made,* but briefly it can be said that economizer troubles predominate in Group A, whilst in Groups B and C the economizer items are largely leakages and the air-heater items are "fouling." As the total number in this class represents under 5% of the whole, the two were combined, but experiences with air-heaters in recent years have indicated the necessity for recording them separately in future.

(5.4) Item 6—Fans and Dampers

This item ranks higher in the proportion of failures than would be expected, but it is conspicuous in the 5-year summary. The number of failures rose from 17 in 1938 to 97 in 1941. The combined influence of loading and state of the flue gases regarding entrained grits has resulted in a type of extensive erosion of fan blades and casings not previously experienced.

(5.5) Item 7—Stoker Drive

The breakdowns per boiler are roughly the same in Groups A and B. In Group C they are appreciably higher, largely owing to "teething" troubles. It will be noted that 15 boilers were com-

* Similarly the records available do not permit the separation of pulverized-fuel equipment.

Table 2

Breakdown Analysis 1938–1942

Item	Pre-1930 plant							1930–1937 plant							1938–1942 plant							A + B + C							Per cent of total
	Group A 150–275 lb/in²					5-year period		Group B 300–600 lb/in²					5-year period		Group C 300–600 lb/in²					5-year period		All groups					5-year period		
Group and year	38	39	40	41	42	Total	Breakdowns per plant item	38	39	40	41	42	Total	Breakdowns per plant item	38	39	40	41	42	Total	Breakdowns per plant item	38	39	40	41	42	Total	Breakdowns per plant item	
Output (millions)	850	802	954	1032	956	4594		1217	1332	1236	1224	1237	6246		—	396	779	1036	1431	3642		2077	2530	2969	3290	3615	14481		
Average plant running load factor	41	38	46	60	56	47%		81	78	84	85	97	85%		—	95	78	80	90	89%		56	59	63	70	77	66%		
No. of boilers	106	106	107	104	104	—		25	25	25	25	25	—		—	6	8	13	15	—	*	131	137	140	142	144	—		
No. of turbines	57	57	58	58	58	—		10	10	10	10	10	—		—	1	4	6	9	—		67	68	72	74	77	—		
Total main plant items	163	163	165	162	162			35	35	35	35	35			—	7	12	19	24			198	205	212	216	221			
Boiler — 1. Superheaters	12	13	13	7	17	62	0·59	2	4	1	8	3	18	0·72	—	3	1	—	8	12	1·43	14	20	15	15	28	92	0·66	3·4
Boiler — 2. Boiler tubes, drums and ranges	12	29	46	59	70	216	2·06	6	8	11	11	10	46	1·84	—	2	11	5	17	35	4·17	18	39	68	75	97	297	2·14	10·9
Boiler — 3. Stokers and brickwork	80	77	158	172	123	610	5·8	15	10	28	64	44	161	6·44	—	7	24	12	20	63	7·50	95	94	210	248	187	834	6·01	30·6
Boiler — 4. Economizers and air-heaters	6	5	15	4	22	52	0·5	21	8	9	7	5	50	2·0	—	4	6	5	12	27	3·21	27	17	30	16	39	129	0·93	4·7
Boiler — 5. Feed pumps and ranges	6	3	5	7	6	27	0·26	—	1	1	—	—	2	—	—	1	1	—	—	2	—	6	5	7	7	6	31	0·22	1·1
Boiler — 6. Fans and dampers	10	20	21	65	53	169	1·61	7	11	15	28	23	84	3·36	—	—	6	4	5	15	1·79	17	31	42	97	81	268	1·93	9·8
Boiler — 7. Stoker drive	14	10	30	24	54	132	1·26	4	2	3	14	7	30	1·2	—	4	4	3	6	17	2·02	18	16	37	41	67	179	1·29	6·6
Turbo-alternator — 8. Governor and valve gear	9	21	16	16	29	91	1·57	4	2	5	6	6	23	2·3	—	4	2	5	8	19	4·75	13	27	23	27	43	133	1·86	4·9
Turbo-alternator — 9. Oil pumps and lubrication system	5	7	19	15	19	65	1·12	8	3	5	2	8	26	2·6	—	9	1	2	1	13	3·25	13	19	25	19	28	104	1·45	3·8
Turbo-alternator — 10. Oil coolers	2	5	1	1	2	11		—	—	1	1	—	2		—	—	—	—	—	—		2	5	2	2	2	13		0·5
Turbo-alternator — 11. Stator	—	5	2	1	3	11	0·91	2	1	1	—	—	4	2·3	—	—	—	—	—	—		2	6	3	1	3	15	1·08	0·5
Turbo-alternator — 12. Rotor and slip-rings	2	1	1	2	—	6		—	1	—	1	2	4		—	—	—	—	—	—		2	2	1	3	2	10		0·4
Turbo-alternator — 13. Excitor	9	7	4	10	6	36		1	2	3	4	5	15		—	—	1	—	—	1		10	9	8	14	11	52		1·9
Circ. water and condenser — 14. Circ. water pumps	7	6	7	11	3	34		4	—	2	1	—	7		—	—	—	—	—	—		11	6	9	12	3	41	0·57	1·5
Circ. water and condenser — 15. Pump motors	3	—	1	2	—	6		1	—	—	—	—	1		—	—	—	—	—	—		4	—	1	2	—	7		0·3
Circ. water and condenser — 16. Circ. water pipework and valves	2	1	7	3	1	14		1	2	—	—	1	4		—	—	—	—	—	—		3	3	7	3	2	18		0·7
Circ. water and condenser — 17. Ejectairs and extraction pump	6	8	15	9	19	57	0·98	1	3	3	3	—	10	1·0	—	—	—	—	—	—	—	7	11	18	12	19	67	0·94	2·5
Circ. water and condenser — 18. Condenser fouling	6	7	14	15	8	50	0·86	—	2	1	5	3	11	1·1	—	—	—	1	—	1	—	6	9	15	21	11	62	0·87	2·3
Circ. water and condenser — 19. Condenser leakage	13	16	21	36	51	137	2·36	9	1	8	5	5	28	2·8	—	—	—	9	15	24	6·0	22	17	29	50	71	189	2·64	6·9
20. Miscellaneous (on ancillary plant)	21	16	15	40	32	124	0·76	1	7	6	11	11	36	1·03	—	2	7	9	4	22	1·77	22	25	28	60	47	182	0·87	6·7
Total breakdowns	225	257	411	499	518	1910	11·72	87	68	103	171	133	562	16·06	—	36	64	55	96	251	20·24	312	361	578	725	747	2723	12·94	100%
Boiler breakdowns	140	157	288	338	345	1268	12·08	55	44	68	132	92	391	15·64	—	21	53	29	68	171	20·36	195	222	409	499	505	1830	13·18	67·1%
Turbine-room breakdowns	64	84	108	121	141	518	8·93	31	17	29	28	30	135	13·5	—	13	4	17	24	58	4·68	95	114	141	166	195	711	9·93	26·2%

* This column corrected *pro rata* for 5-year comparison.

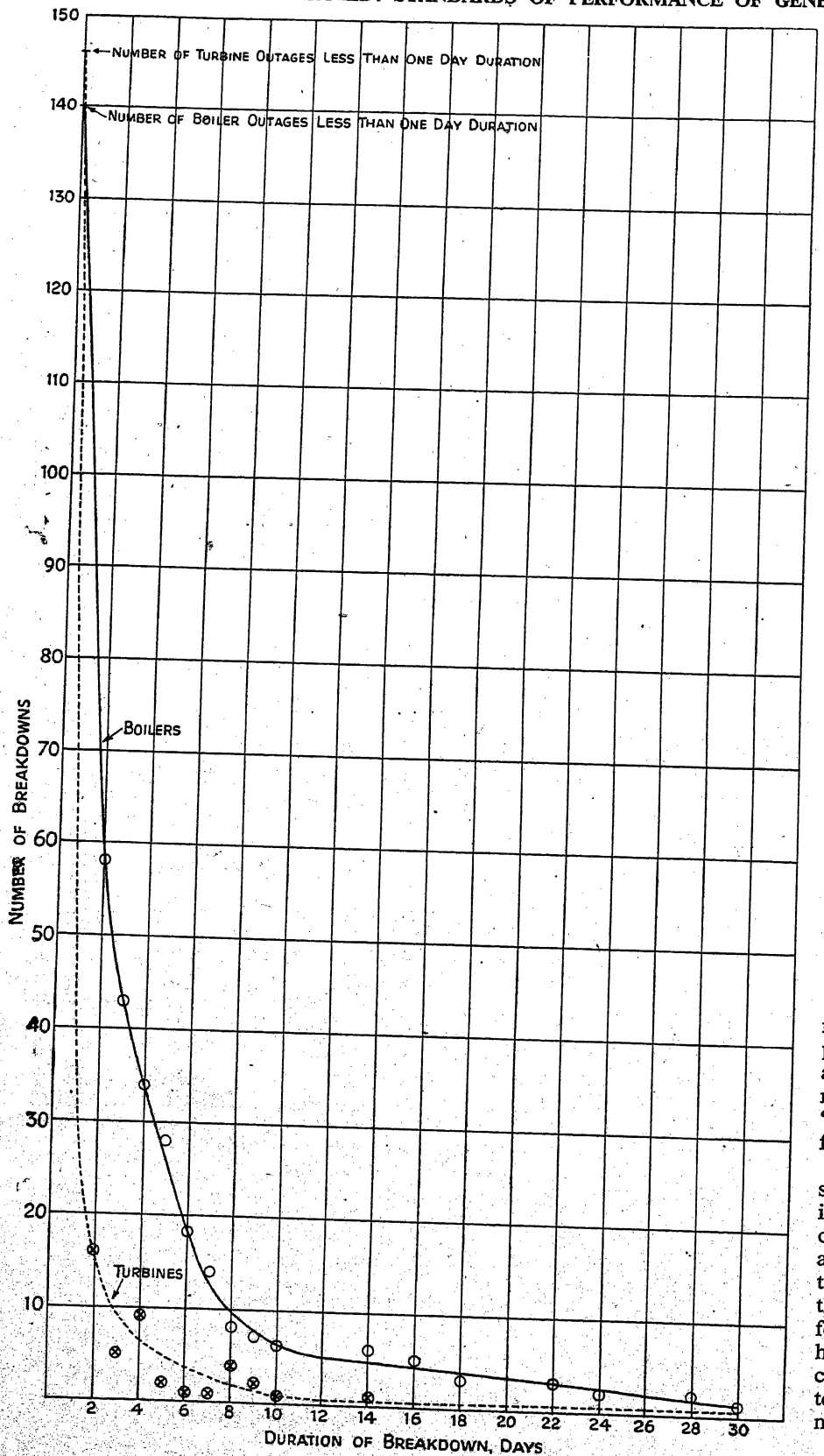


Fig. 3.—Analysis of plant breakdowns, 1942.

missioned in this group during the four years. One would not anticipate a continuance of stoker-drive troubles when all the new boilers had passed through the makers' maintenance period.

(5.6) Items 18–19—Condensers

An appreciable proportion of breakdowns fall under Items 18 and 19. It will be observed that Group B has 3·9 breakdowns per condenser compared with 3·2 in Group A. It is considered that, had the two groups been of the same age, Group B would have been still higher in relation to Group A, owing to higher loadings. The failures in Group A were partially due to age.

(5.7) Liability to Breakdown

Some derived figures in terms of units output and average value of a failure have been computed to estimate the liability to rate of breakdown. During the whole period the average plant running load factor was 66%, rising from 56% in 1938 to 77% in 1942, and for each 5·32 million units generated a failure of some kind has occurred on a boiler, turbine or section of auxiliary plant. Main items of plant have incurred on the average a loss of capacity by breakdown every 4·63 months.

Fig. 4 is a graphical representation of selected items from Table 2, showing the average operating periods of freedom from breakdown. The periods have been deduced from the total breakdowns in each class. Other indices may be derived by careful analysis, and the information may be of value to designers as well as operators in indicating the component which merits improvement in design or manufacture to achieve the best possible combined availability. Two sets of derived figures appear in Table 2A.

(6) AVAILABILITY OF PLANT

Outages due to annual overhauls are not shown in Table 2. Taking all outage periods into consideration, the annual availability of stations in the groups under review is shown in Table 3. [The term "availability" is computed by means of formula (1) in Section 7.8.]

All three groups of plant have been subjected to average loading higher than in past years. Owing to improvements in design and manufacture, the more recent and the new plant would be expected to give a better availability than some of the older plant which has been in service for 15 to 20 years. The older plant has, however, been kept in good serviceable condition by suitable repairs and maintenance, and still gives a good performance.

The dispersals of annual availabilities are shown against average plant running load factor in Table 3, and point to the conclusion that the lower-pressure plant of older design is incapable of maintaining the higher outputs of the more modern plant over the 12 months without excessive loss of availability.

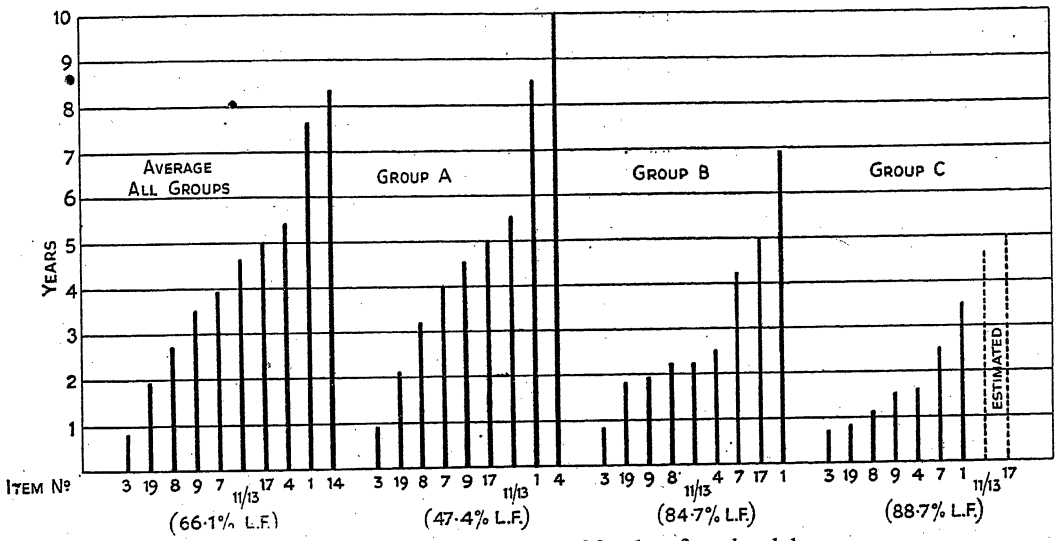


Fig. 4.—Average operating periods of freedom from breakdown.

1. Superheaters.
3. Stokers and brickwork.
4. Economizers and air-heaters.
7. Stoker drive.
8. Turbine governor and valve gear.
9. Oil pump and lubrication system
11-13. Main alternator and exciter.
14. Circulating-water pumps.
17. Ejectairs and extraction pumps.
19. Condenser leakage.

Table 2A

Item	Group A L.F. = 47·4%		Group B L.F. = 84·7%		Group C L.F. = 88·7%	
	Turbines	Boilers	Turbines	Boilers	Turbines	Boilers
Output between breakdowns, kWh × 10^6 ..	8·86	3·63	46·2	16·0	62·8	21·25
Output per MW per breakdown, kWh × 10^6 ..	1·5	1·05	1·76	1·31	2·03	1·24

The lower-pressure plant (Group A) installed before 1930 (pressure 150–275 lb/in^2) of which there are 83 annual observations, was designed to suit the load curves of the undertakings for the period when the annual load factors were of the order of 30–40%. The weighted average performance of these stations was 71·8% availability at 47·4% load factor.

This type of plant, therefore, is better placed under Grid operation on a 1- or 2-shift cycle, which it usually fulfils. In this way it is operated more nearly to its designed load factor and gives annual availabilities comparable with the more modern plant.

The availability of plant installed between the years 1930 and 1937 (Group B), of which there are 24 observations, relates to a period when 400- and 600-lb/in^2 plants were becoming more generally employed. At that time the performance of the new designs (in view of their higher pressures and temperatures) was open to question and it was thought that lower reliability might result.

This plant gave 71·5% availability at 84·7% load factor.

The plant installed after 1938 (Group C), of which there are also 24 station records, show still better performance, with weighted average availability of 79·9% at 88·7% load factor. Boiler plant installed during this period was designed almost entirely in accordance with a specified clause stipulating that after a 6 months' period of commercial load the boiler should at full-load test show an efficiency within 3% of the guarantee on stoker-fired boilers and within 2½% on pulverized-fuel boilers.

In Group A and a portion of Group B plant it is recognized that better all-round results might be achieved by suitable modifications. For example, the fitting of extra or improved draft regulation, soot-blowers or water-lancing equipment, or the improvement in design of air-heaters, or possibly in some cases their elimination.

Such projects would be examined in the light of the proposed generation programme.

(7) STANDARDS OF PERFORMANCE AND ADJUSTMENTS FOR RUNNING CONDITIONS

Standards of performance have risen considerably in recent years. This is conspicuous in single stations operating at two different pressures with plant differing in age by 10 years.

Results in general, however, vary considerably between one station and another for many reasons, e.g. reliability or design embellishments which do not fulfil their early promise. There is also the varying skill with which operating staffs discharge their duties.

The foregoing provides sufficient data, typical of general performances, to demonstrate the state of technique and performance between the three groups of plant under review. It is therefore possible to suggest standards of performance for each.

Enhanced utilization of available heat drop, larger units of plant, invention, design and application of new instruments, better loading conditions and the skilled supervision and operation of the modern plant, have focused most attention on the performance of the newer stations. The excellent results obtained in some of the "lower-grade" stations is often overshadowed by the former.

There is little doubt that in due course many of these lower-grade stations will be modernized with higher-grade plant, but meantime, although smaller than the more modern stations, their contribution to the generation requirements of the country is considerable and of great importance. It follows that a high standard of performance in their class is required.

In the authors' view, the "standard merit" of a generating station should include two factors, (*a*) the availability of the plant, and (*b*) the operating efficiency (as distinct from thermal efficiency), the product of these two results being regarded as representing the overall "standard merit" of the station performance.

In his Inaugural Address[1] before The Institution in October, 1939, the President said "it is customary to express thermal efficiency as one overall figure, but as we are approaching the limiting ideal efficiency obtainable with steam generation, it might be well to separate out three factors—ideal efficiency, maximum plant efficiency and operating efficiency."

The ideal efficiency is calculable from steam and heat-drop tables and has been dealt with in papers and discussions of the various Institutions from time to time. In a discussion[2] before The Institution of Civil Engineers in June, 1938, a basis was described for calculating the ideal efficiency. The method was dealt with fully in a paper by J. F. Field.[3]

In the Thomas Hawksesley lecture[4] before The Institution of

Table 3

RELATION BETWEEN ANNUAL AVAILABILITY AND LOAD FACTOR (ZONAL DISPERSION OF OBSERVATIONS)

		Group A: Plant commissioned 1920–1929 (150–275 lb/in²)												Group B: Plant commissioned 1930–1937 (300–600 lb/in²)												Group C: Plant commissioned 1938–1943 (300–600 lb/in²)											
	Load factor	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	Total	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	Total	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	Total
Availability 40-50		—	2	—	—	—	—	—	—	—	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
50-60		—	3	3	—	—	—	—	—	—	6	—	—	1	2	2	—	—	—	—	5	—	—	—	—	—	—	—	—	—	—
60-70		—	9	10	2	1	—	—	—	—	22	—	—	2	2	5	—	—	—	—	7	—	1	4	—	—	—	—	—	—	5
70-80		6	6	13	4	1	2	—	—	—	32	—	—	—	1	2	—	—	2	5	7	—	—	—	—	—	—	—	—	—	—
80-90		—	3	5	8	3	—	—	—	—	19	—	—	—	—	1	2	2	—	5	5	1	2	2	4	2	—	1	3	—	13
90-100		—	—	—	1	1	—	—	—	—	2	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	1	1	5
Total observations ..		6	23	31	15	6	2	—	—	—	83	—	—	1	5	11	3	2	2	—	24	2	1	6	4	3	1	2	4	1	24
kW weighted average availability		71·8% at 47·4% l.f.										Average availability 71·5% at 84·7% l.f.										Average availability 79·9% at 88·7% l.f.									

Mechanical Engineers in January, 1940, a convenient method is described which takes account of 7 stages of feed-heating in finite stages of 50 deg. F rise.

The figures derived by these alternative methods differ to a small degree, and the last-mentioned tends to give a slightly lower ideal efficiency than the former, which takes into account an infinite number of stages of feed heating. For the authors' purpose either method can be adopted.

The method giving the lower ideal thermal efficiency has been chosen for the example, in preference, as one most simulating practical conditions. A system is then evolved by which comparisons of actual thermal efficiency for any period can be made with a practical standard of maximum probable efficiency.

The actual performance of plant compared with a proper standard in this way provides a basis for the analysis of the causes of deficiencies in plant performance. Whilst it is probable that such practice is already adopted by many stations, there appears to be no common standard method at present in use with which to make comparisons.

(7.1) Operating Efficiency

It has not been usual practice in power station records, or in published statistics, to indicate "operating efficiency." It has been usual in the Electricity Commissioners' returns to show, amongst other things, details of operating costs and thermal efficiency. With advancement in design of steam-raising plant using higher pressures and temperatures there is a considerable diversity of thermal performance efficiency. The older types of plant with their low thermal efficiencies may appear to be a poor standard compared with the more modern plant operating at about 25–27% sent out. Nevertheless, they are showing a performance relatively as good as those operating at the higher pressures.

The authors consider that an additional factor should be brought into the records, namely the "operating efficiency." This term has been defined as:—

$$\frac{\text{Actual thermal efficiency}}{\text{Maximum probable thermal efficiency}}$$

In calculating the maximum probable efficiency of a generating station under its running conditions the following factors (*a*) to (*e*) should be taken into account:—

(*a*) Steam pressure and temperature and feed-water temperature.
(*b*) Vacuum.
(*c*) Overall efficiency ratio.
(*d*) Running plant load factor.
(*e*) Banking coal.

Other operating conditions to be considered are:—
(*f*) Losses due to starting up.
(*g*) Raising steam in banked boilers.
(*h*) Boiler plant brought up from cold.
(*j*) Load-changes.
(*k*) Low superheat and delayed boiler efficiency.
(*l*) Effect of age of plant.

The effect of the adjustments for the factors (*f*) to (*l*) inclusive, which would not differ much between stations, has been found to be relatively small.

For instance, if claims are made for extra allowances (to account for adverse conditions) it would be difficult to justify any adjustments exceeding the following:—

(*f*) Starting up combined plant from cold	7 cwt per MW of plant capacity
(*f*) Starting turbine only from cold	0·5 cwt per MW of turbine capacity

(*g*) Raising to range pressure from banked condition (in addition to banking allowance)	0·08 cwt per MW equivalent
(*h*) Starting boiler only from cold	6·5 cwt per MW of capacity (evaporation equivalent)
(*j*) Load changes directed without notice (N.B. the load change is presumed to be 20% of boiler rating)	Effect of reducing target by $\frac{0{\cdot}033C}{H}$% where C = number of such load changes, H = running hours
(*k*) Adverse conditions at turbine stop valve, when loading from cold start	[see formula below (compute fuel equivalent as per extra rate)]
(*l*) Ageing	Small and variable —recommend test.

Formula for (*k*) above: $R_A = R_T \times \frac{H}{H - 0{\cdot}07N}$

where R_T = normal heat rate.
R_A = adverse heat rate.
H = running hours.
N = number of starts.

Applied to an example for a curtailed running station where the conditions were particularly adverse, the operation efficiency becomes 76·0% instead of 74·5% as returned by the proposed method. The extra fuel accounted for was 25·5 tons of a total consumption of 1 467 tons, the banking allowance being 136·5 tons, i.e. the banking allowance represents 84·3% of the total allowances.

The authors are of the opinion that for comparative purposes items (*f*) to (*l*) can be neglected. Items (*a*) to (*e*) inclusive, however, which may vary considerably between stations according to their operating conditions, need to be taken into account for equity.

(7.2) (*a*) Heat Cycle—Steam Pressure and Temperature, etc.

The "ideal efficiency" calculated is a theoretical one and does not take into account the actual boiler and turbine efficiencies obtained in practice.

(7.3) (*b*) Vacuum

The actual vacuum for which the plant is designed is employed in the main calculation.

(7.4) (*c*) Efficiency Ratio

To account for boiler and turbine efficiencies an efficiency ratio is introduced. This is a multiple of the maximum boiler and turbine efficiencies achieved in past years. Fig. 6 gives the maximum attained efficiency ratio of plant according to the date of installation.

(7.5) (*d*) Load-Factor Correction

The proper basis would appear to be the "running plant load factor." The maximum efficiency of any plant would, according to design, be obtained only at maximum turbine and boiler efficiencies (usually about 80% of M.C.R.).

To apply the correction to a station of various turbine sizes, the load factor is obtained as follows:—

$$\text{Load factor} = \frac{\text{Units generated} \times 100}{\text{Sum (M.C.R. of each machine} \times \text{its running hours)}}$$

Load factor corrections have been computed for various turbine sizes (with appropriate boiler backing) and plotted in Fig. 5.* The formula used in this figure has been checked during acceptance tests of plant. The discrepancy was found to be negligible for over half the scale and at no point did it exceed 2%.

(7.6) (*e*) Banking

All stations, whether 1-, 2- or 3-shift, incur banking losses; the banking of boilers is essential to the operating programme for reasons of security, and predominates in 1- and 2-shift stations.

It would not seem equitable to debit such losses against station performances, and allowances of fuel are proposed for this purpose. For the older types of plant (Groups A and B) with inferior draught-control devices, the allowance suggested is 0·5 cwt per 10 000-lb boiler capacity per hour of banking.

For the more modern equipment, including powdered-fuel plant (Group C), the allowance would be 0·3 cwt per 10 000 lb/hour, these figures being supported by tests. The allowances exceed the calculated radiation and stack loss and are based upon the differing efficiency of restoration of the lost heat.

It is realized that banking practice is by no means uniform, depending as it does upon the type of furnaces and damper arrangements, fuel characteristics, etc., and it may be that the allowances are to the slight advantage of some stations. In determining the "actual thermal efficiency," therefore, the banking allowance (from the banking hours) should be deducted from the total coal consumed.

(7.7) Routine Calculations

The calculations are relatively simple and, once the basic data have been determined, are speedily done.

(*a*) *Ideal Efficiency.*

Obtained from curves and tables (*Proceedings of The Institution of Mechanical Engineers*, 1940, **142**, No. 4).

(*b*) *Efficiency Ratio.*

Obtained from Fig. 6 according to the year of *installation* of the plant.

(*c*) *Maximum Probable Efficiency* (80% *load factor*).

Ideal efficiency × Efficiency ratio

(*d*) *Maximum Probable Efficiency corrected for Running Plant Load Factor.*

Item (*c*) × load-factor correction from Fig. 5.

(*e*) *Minimum Probable Heat Rate corrected for Running Plant Load Factor.*

$$\text{B.Th.U./kWh generated} = \frac{3{,}412 \times 100}{\text{Item (}d\text{)}}$$

(*f*) *Steaming Coal.*

Coal consumption − Banking coal (tons).

(*g*) *Actual Heat Rate.*

$$\text{B.Th.U./kWh generated} = \frac{\text{Item (}f\text{)} \times \text{Calorific value} \times 2\,240}{\text{Units generated}}$$

(*h*) *Operating Efficiency.*

$$\frac{\text{Item (}e\text{)} \times 100\%}{\text{Item (}g\text{)}}$$

* If the correction curve for a particular plant has been independently established it would be proper to substitute it, but for the sake of uniformity and for those cases in which the corrections are unknown, Fig. 5 is offered as providing data sufficiently accurate for the purpose required.

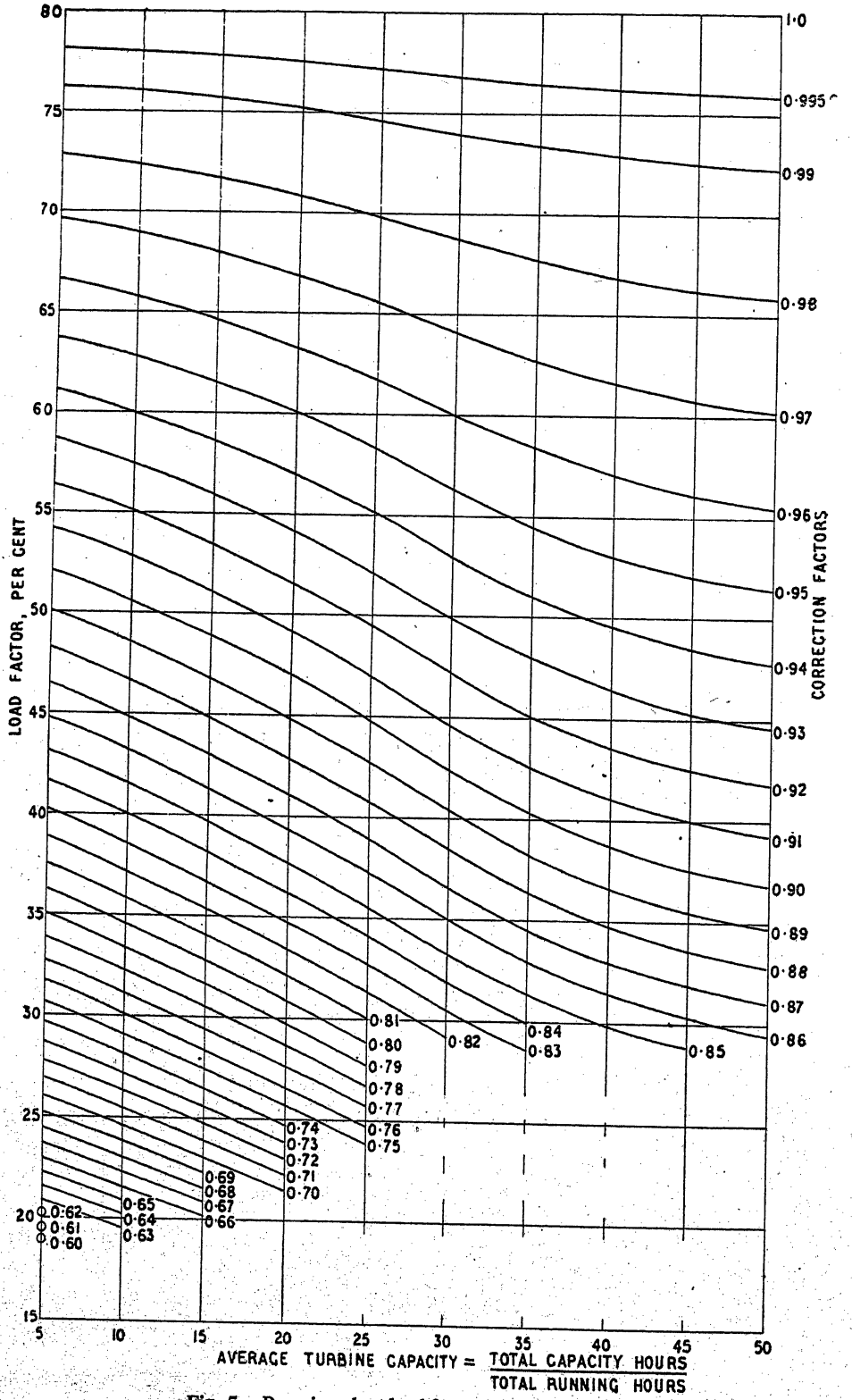


Fig. 5.—Running plant load factor correction curves.

$$\text{Efficiency factor} = \frac{0{\cdot}0125F + K}{FIL + K}$$

Plant, MW ..	5	10	15	20	25	30	35	40	45	50
F, %	16·8	15·4	14·0	12·6	11·2	9·9	9·08	8·26	7·87	7·49
K, %/% ..	0·805	0·818	0·832	0·845	0·859	0·871	0·879	0·887	0·891	0·895

Table 4

Monthly Station Operating Efficiency

	H.P. Section	L.P. section (*a*)
1. Total machine capacity-hours, sum (M.C.R. of each machine × its running hours)	_____MWh	_____MWh
2. Total machine running-hours	_____hours	_____hours
3. Equivalent single generator (average turbine capacity for Fig. 5) Item 1/Item 2	_____MW	_____MW
4. Total units generated	_____MWh	_____MWh
5. Running load factor, (Item 4 × 100)/Item 1	_____%	_____%
6. Load-factor correction (Fig. 5 and Items 3 and 5)	_____	_____
7. Maximum probable efficiency (constant)	_____%	_____%
8. Target efficiency, Item 7 × Item 6	_____%	_____%
9. Target heat rate, (3 412 × 100)/Item 8	_____B.Th.U./kWh	_____B.Th.U./kWh
10. Combined target heat rate, (Item 9 × Item 4) + (Item 9*a* × Item 4*a*)/(Item 4 + Item 4*a*)	_____B.Th.U./kWh	
11. Total fuel consumed	_____tons	
12. Total boiler capacity-hours banked (I) "Modern" blrs. = _____lb-hr × 10^3. (II) "Old" blrs. = _____lb-hr × 10^3		
13. Banking allowance, (Item 12 (I) × 1·5/1 000) + (Item 12 (II) × 2·5/1 000)	_____tons	
14. Steaming coal, Item 11 — Item 13	_____tons	
15. Actual heat rate (Item 14 × 2 240 × C.V. of fuel)/(Item 4 + Item 4*a*)	_____B.Th.U./kWh	
16. Operating efficiency, Item 10/Item 15	_____%	

If h.p. and l.p. fuel can be separated, Items 11 to 16 can be calculated independently for each pressure in addition to the combined figure.

Return for month of_____19____ Station_____

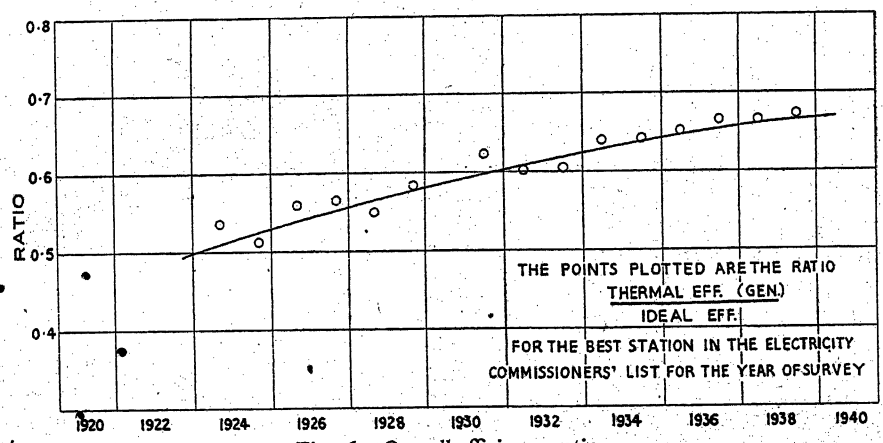


Fig. 6.—Overall efficiency ratio.

Items (*a*)–(*e*) above are fixed for each type of plant, and once they have been determined they form the basic data on which routine calculations are made.

Table 4 is the type of schedule which can be used for preparing operating efficiency data monthly for a station with two pressures.

Fig. 7 shows the monthly operating efficiencies of a group of stations for the year 1942. Calculations for all subsidiary items, except banking coal, have been excluded.

Some of the irregularity in these results is due to inaccurate coal measurement. The variable results are worth further consideration; and it is recommended that the causes of a decline from "maximum probable efficiency" should be analysed (see Appendix, formulae 7–10*a*).

Table 5 is an example of the probable items which would cause a decline in operating efficiency. Values have been allocated to some of them and the effects are summarized in Table 6, which gives alternative segregations.

The value to operating staffs of preparing a schedule of items for constant observation is apparent if improvements in performance are to be sought. To be kept constantly advised of all deficiencies without special tests and calculations would need more instruments than are readily available in all stations to-day, and there is yet much to be done in this direction to aid the efficiency and combustion engineer.

It may be that structural alterations to boilers or other sections of the plant are indicated, the cost of which should then be balanced against the value of the gain in operating efficiency (see formulae 2 and 3). Correct analysis of the causes of the deficiency is the first step to better performance (see Table 5, also formulae 7–10*a* in Appendix).

(7.8) Maximum Probable Availability

The importance of high availability lies chiefly in the saving of overhead costs. High availabilities which can be relied upon will mean that a smaller total plant capacity will suffice for the load.

Table 5

ANALYSIS OF CONTROLLABLE CAUSES OF DEFICIENCIES IN THERMAL PERFORMANCE (RADIATION, BANKING, LOW PRESSURE AND TEMPERATURE EXCLUDED)									CATEGORY OP=OPERATION M=MAINTENANCE C=COAL A=ALTERATIONS	POINTS ON THERMAL EFFICIENCY SCALE	POINTS ON OPERATION EFFICIENCY SCALE	
FAILURE TO PRODUCE HEAT FROM C.V. OF FUEL	RIDDLINGS F_1	F_{1a}	UNSUITABLE OR DEFECTIVE GRATE LINKS					F_{1a}	M	0·10	0·43	1·72
		F_{1b}	EXCESSIVE FINES OR DRYNESS					F_{1b}	C & OP	0·31	1·29	
	IMPERFECT COMBUSTION OF VOLATILE CONTENT F_2		LATE DISTILLATION	F_{2a}	ARCH CONTOUR AND HEIGHT			F_{2a}	A	IN F_{2b}	IN F_{2b}	
				F_{2b}	ARCH LENGTH/DEAD PLATE LENGTH/GRATE LENGTH (RATIOS)			F_{2b}	A	0	0	
		F_{2c}	COMBUSTION	TEMPERATURE	INJUDICIOUS REGULATION OF DRAUGHT OR FIREBED THICKNESS GRATE SPEED OR BOILER DUTY			F_{2c}	OP	0·71	2·95	
				TURBULENCE								
				TIME								
	IMPERFECT COMBUSTION OF FIXED CARBON CONTENT F_3	F_{3a}	SHORTAGE OF FORCED DRAUGHT OR POWER AT MOTORS					F_{3a}	A	0	0	4·97
		F_{3b}	FUEL CHARACTERISTIC UNSUITABLE (PROXIMATE ANALYSIS)					F_{3b}	C	0·24	1·03	
		F_{3c}	PROMISCUOUS MIXING OF GRADES					F_{3c}	C & OP	0·40	1·69	
		F_{3d}	HIGH ASH CONTENT OR LOW FUSION TEMPERATURE					F_{3d}	C	0·54	2·25	
FAILURE TO ABSORB HEAT PRODUCED	PORTION OF STACK LOSS ABOVE DEWPOINT TEMPERATURE B		GAS VELOCITY	B_a	CONTROLLABLE PORTION OF FUEL/AIR RATIO AS PER F_{2c}			B_a	OP	0·14	0·58	0·21
		B_b	INFLEXIBLE FAN DUTY CONTROL					B_b	A	0	0	
		DEFECTIVE EQUIPMENT	BAFFLES	B_c	LEAKING			B_c	M	0·040	0·17	
				B_d	PRODUCING UNDUE DRAUGHT GRADIENT			B_d	M	0	0	
			DAMPERS	B_e	LEAKING			B_e	M	0·010	0·04	
				B_f	INADEQUATE CONTROL			B_f	A	0·010	0	
			CASINGS	B_g	BLOWING OUT			B_g	M	0	0	
				B_h	INFILTRATION			B_h	M	0	0	
		FOULING OF HEATING SURFACES	EXTERNAL	B_i	INSUFFICIENT OR INEFFECTIVE SOOTBLOWING			B_i	OP & M	0·57	2·37	7·95
				B_j	OVERLOADING FURNACE VOLUME WHEN USING HIGH VOLATILE COAL			B_j	OP & C	0·20	0·83	
			INTERNAL	B_k	FAULTY PRE CONDITIONING OF FEED (SEE T_{2d})			B_k	OP	0·400	1·67	
				CONCENTRATES IN DRUM WATER	B_l	INSUFFICIENT OR IRREGULAR BLOWDOWN		B_l	OP	0·74	3·08	
					B_m	INCORRECT SOLUBILITY RATIOS		B_m	OP	IN B_j	IN B_j	
FAILURE TO UTILISE HEAT ABSORBED	TURBINE PLANT T_1	BLADE AND GOVERNOR SYSTEM	T_{1a}	EARLY OPENING OF, OR ILL SEATING OF VALVES				T_{1a}	M	0	0	3·17
			T_{1b}	EXCESSIVE CLEARANCES				T_{1b}	M	0	0	
			T_{1c}	DEFECTIVE DIAPHRAGM PACKINGS				T_{1c}	M	0	0	
			T_{1d}	EROSION OR CORROSION OF BLADES				T_{1d}	M	0	0	
			T_{1e}	DEPOSITS ON BLADING DUE TO CARRY-OVER				T_{1e}	OP	0·20	0·83	
		GLAND SYSTEM	T_{1f}	MECHANICAL CONDITION				T_{1f}	M	0	0	
			T_{1g}	STEAM REGULATION OR FAILURE TO RECLAIM MAX. HEAT FROM LEAK-OFFS				T_{1g}	OP	0·010	0·04	
		FEED HEATERS	T_{1h}	FOULING OR FLOODING (ASSOCIATED WITH T_{2d}) AND TRAPS				T_{1h}	OP & M	0·010	0·04	
			T_{1i}	BY PASSING OF DRAIN COOLER				T_{1i}	OP	0	0	
			T_{1j}	INADEQUATE VENTING PIPES AND VALVES (ASSOCIATED T_{2e} AND PART T_{2f})				T_{1j}	A	0	0	
	CONDENSING PLANT AND C.W. SYSTEM T_2	LOW VACUUM	T_{2a}	EXCESSIVE FRICTION IN STEAM SPACE (TOO LIBERAL COOLING SURFACE)				T_{2a}	A	0	0	
			T_{2b}	FOULED TUBES OR TUBE PLATES				T_{2b}	OP & M	0·56	2·33	
			T_{2c}	INSUFFICIENT CIRCULATING WATER OR HIGH INLET TEMPERATURE				T_{2c}	OP	0·200	0·84	
			EXCESSIVE PARTIAL PRESSURE OF INCONDENSIBLES IN STEAM SPACE AND APPARENT UNDERCOOLING OF CONDENSATE	T_{2d}	LEAKAGE OF C.W. TO STEAM SPACE (ASSOCIATED T_{1h} - FOULING AND B_K) ※			T_{2d}	M	0	0	
				T_{2e}	FAULTY EJECTAIRS			T_{2e}	M	0	0	
				T_{2f}	AIR LEAKAGE AT ANY POINT AFTER ZERO PRESSURE IS REACHED IN TURBINE OR CONDENSER			T_{2f}	M	0	0	
				RECEIVED WITH MAIN STEAM	T_{2g}	FAULTY CLOSED FEED SYSTEM		T_{2g}	M	0	0	
					T_{2h}	INADEQUATE DEAERATION OF BOILER FEED		T_{2h}	OP & A	0	0	
		HIGH VACUUM	T_{2i}	EXCESSIVE LEAVING LOSSES (LOW INLET TEMP. EXCESSIVE C.W. DURING LIGHT LOADS)				T_{2i}	OP	0	0	
			T_{2j}	REAL UNDERCOOLING OF CONDENSATE				T_{2j}	OP	0	0	
MISCELLANEOUS LEAKAGES INCLUDING MAKE-UP, STARTING, EXCESSIVE SOOT BLOWING ETC.									M	0·37	1·54	
									DEFICIENCY	5·76%	24%	
									OBTAINED	18·24%	76%	
									MAX. PROBABLE	24·00%	100%	

※ THE EFFECTS OF B_K B_l B_m T_{1e} T_{1h} FOLLOW QUICKLY, DETRACTING FROM BOTH TURBINE & BOILER AVAILABILITY. THE QUANTITY OF UNDEAERATED WATER ADMITTED, IF SLIGHT MAY NOT AFFECT VACUUM - EXTERNAL FOULING OF A PORTION OF CONDENSER TUBES MAY ENSUE, NORMALLY INACCESSIBLE. FOR CLEANING.

With plant costs at £25 per kW, 1 kW improvement in availability at approximately 12% p.a. represents a saving of £3 per annum in capital charges, staffing, maintenance, rates management and insurance which would be incurred if the equivalent new capacity were installed. In the Central Electricity Board's generation programme, low availability of high-efficiency or high-merit plant having low heat costs incurs additional fuel costs owing to the transference of load to much lower-grade plant. Any advance in availability is therefore well worth striving for.

Not only does it improve the overall economic production cost but it must also eventually react beneficially upon all consumers and industry.

The percentage availability of a station may be calculated by the following formula:—

$$\frac{C_{a.m.} + C_{p.m.})}{728 C_i} \quad \text{(for 52 weeks)} \qquad (1)$$

where $C_{a.m.}$ = average capacity available between 6 a.m. and 1 p.m. each day

$C_{p.m.}$ = average capacity available between 2 p.m. and midnight each day

and C_i = average capacity installed.

Thus in the formula for one week only, the denominator becomes $14C_i$.

The night period from midnight to 6 a.m. and the lunch hour are excluded to ensure that if the plant availability coincides with the demand, full credit is shown in the result. There may be some slight advantage in this method to those stations having plant operating for one or two shifts only as compared with those running three shifts with well-loaded plant. To a small degree, it would enable minor adjustments to be made to grate mechanisms, steam joints, etc., and tend to prevent outages during the critical load period of the day. There is no objection,

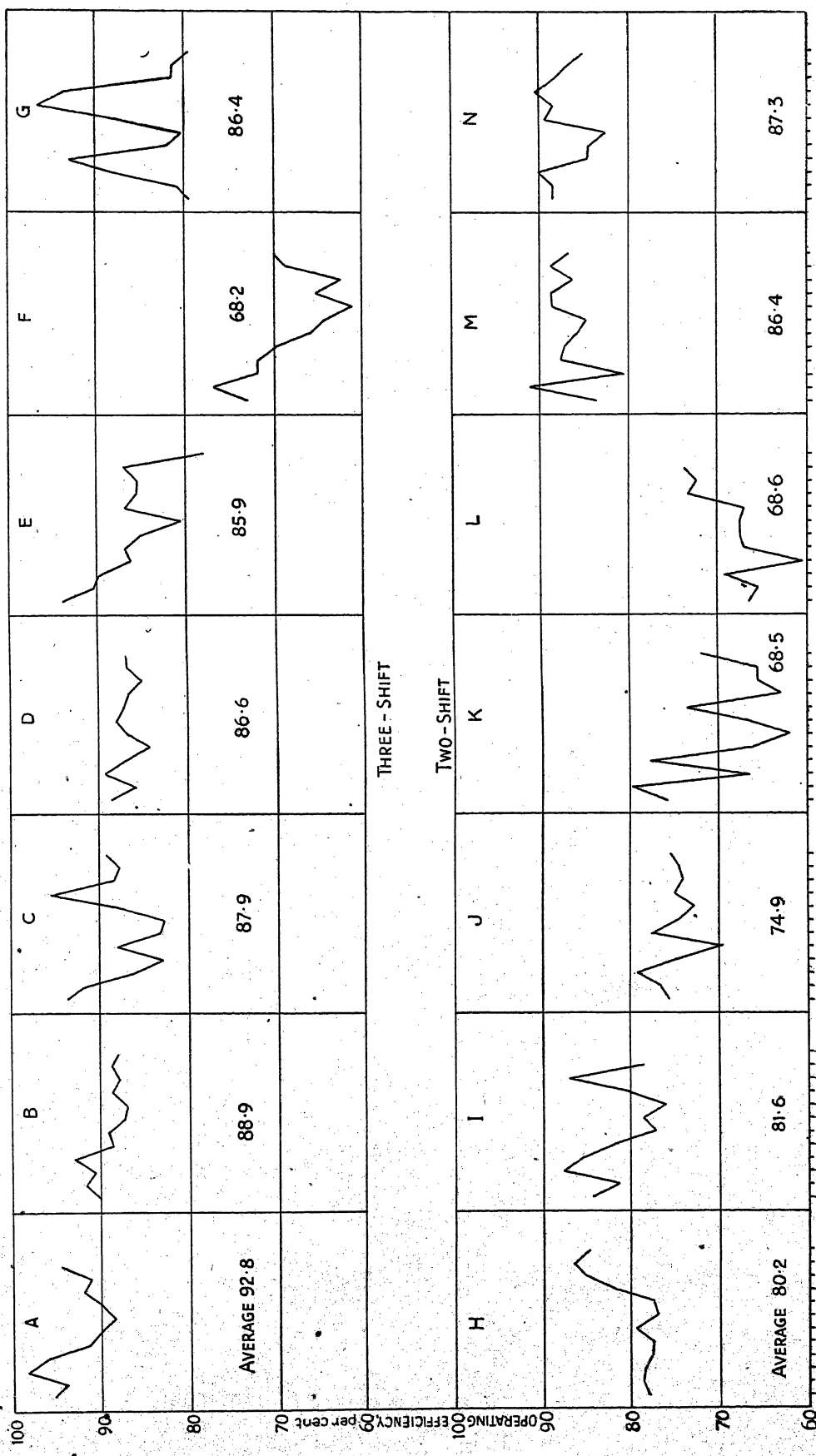


Fig. 7.—Station monthly operating efficiencies for 1942.

Table 6

	Thermal efficiency points		Operating efficiency points	
	%	%	%	%
Present condition		18·24		76
Eliminate "operation" causes	3·46		14·2	
Eliminate "fuel" causes ..	1·3		5·8	
Eliminate "maintenance" causes	1·0	5·76	4·0	24
		24·0		100
Present condition		18·24		76
Corrected furnace conditions	2·32		9·65	
Other boiler-house conditions	2·34		9·75	
Corrected turbine-house conditions	1·10	5·76	4·60	24
		24·0		100

however, to the 24 hours being taken if desired, when the results would be little different.

On the other hand, base-load stations with high load factors have a bigger task in arranging their maintenance work to keep a high availability, but have the advantage at present of more modern plant embodying improvements designed for such high availability.

In over-boilered or over-turbined stations (excess kW capacity of turbines over boilers, or vice versa) it is considered that the availability should be calculated on the basis of the higher kW capacity, otherwise they would have an advantage over those with balanced plant capacities, in achieving high availability, particularly in over-boilered stations.

For suitable standards of availability, in the authors' opinion it would be at present unreasonable to expect annual averages higher than 90%. This would allow all plant in the station to be out in turn for an average period of approximately 5½ weeks. Boiler plant needs an annual overhaul period of from 3–4 weeks, usually during the summer months. Assuming that this can be done on the smaller units in three weeks, a little over a fortnight is left to deal with minor outages on each.

Large units may or may not require longer, and there is occasionally a tendency to omit the "annual" on a turbine if it is running well.

Major breakdowns of plant are likely to occupy much longer periods, depending upon the nature of the breakdown. It would, however, be improper to make allowances for major breakdowns if comparisons of overall performance are to be made. There is still much plant in operation that has never suffered major breakdown.

A figure of 90% availability, and occasionally better than this, is achieved by many stations, and for this reason the authors propose it as one standard for the present. It would, however, seem unfair to expect all types of plant to reach this figure at the higher plant running load factors.

The older plant still in commission but designed and installed in the 1920's at pressures of 150–275 lb/in² was run at load factors much lower than those obtained in modern base-load stations. The manufacturers could then take full advantage of the load curve and the plant was called upon to deal with high output only for short periods of the day.

The average availability of this type of plant in the 5-year period under review shows that with few exceptions the availability falls off considerably with running load factors exceeding 50%.

Nearly all the plant installed in the years 1930 to 1937 inclusive was designed for the higher operating pressures of 300, 400 and 600 lb/in², and on account of its high thermal efficiency was operated on 3 shifts and base loads.

The average availabilities achieved by this plant at running load factors between 50 and 90% are on a par with the lower-pressure plant but are achieved at higher loadings.

Since 1938 and during the 5-year period under review further plant was installed for 300, 400 and 600 lb/in² but of improved design. The average availability achieved by it is still better than that achieved by plant working at similar pressures and installed during the period 1930 to 1937 when operating over a similar range of high load factors.

To determine the maximum standard of performance for each group of plant, the best results in each group have been shown in Fig. 8, all the curves being asymptotic at 90% availability. These

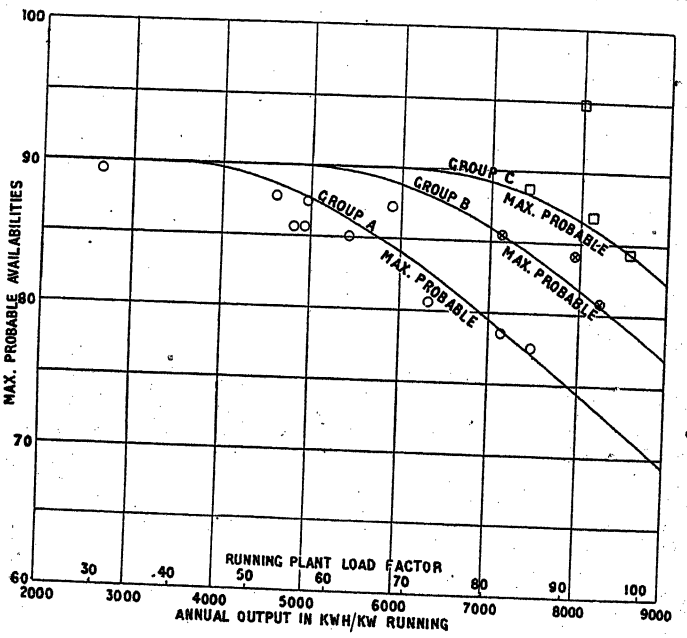


Fig. 8

Load factor should be calculated on available plant if greater than running plant.

curves are considered to be good standards of reference for the purpose intended. If the actual availability of a station is compared with the corresponding value read from the appropriate curve and expressed as a percentage of it, the resultant figure can be used as a factor in the "standard merit" of performance of the station.

(8) VALUE OF INCREMENT OF OPERATING EFFICIENCY

Considerable saving in fuel can be achieved by improvements in operating efficiency on high thermal-efficiency plant, but there are greater savings to be obtained for a given output by similar improvements on the lower-thermal-efficiency plant.

The monetary gain G can be expressed by the formula:—

$$G = \frac{7\,616LC_f(Op_2 - Op_1)}{\eta DOp_1Op_2} \quad . \quad . \quad . \quad (2)$$

in which

G = £ sterling saved per MW of running plant.
L = units output per average kW of running plant in the period.
C_f = fuel cost, in shillings per ton.
η = Maximum probable thermal efficiency expressed as a decimal.
D = calorific value.

Op_1 = lower operating efficiency expressed as a percentage.
Op_2 = higher operating efficiency expressed as a percentage.

(8.1) Value of Increment of Availability

Persistent low availability of plant would incur extensions to total plant capacity for a given load. This would involve additional capital charges, staffing and maintenance costs, rates, management and insurance, which can be expressed in the following formula:—

$$O = \frac{100(IC + F)}{C} \text{ per cent} \quad . \quad . \quad . \quad . \quad (3)$$

where O = overheads.
I = capital charge expressed as a decimal.
C = capital cost per kW of *new* plant.
F = fixed charges per kW in £ per annum for management, rates, wages, insurance, repairs, maintenance, oil, water and stores.

The cost in £ per MW per annum per 1% availability is

$$0{\cdot}1CO \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Comparing the respective savings to be made by availability and operating efficiency, it is often true that the higher savings are made per point increment in operating efficiency, particularly where this is low. It may appear that gains in operating efficiency are preferable to gains in availability and encourage such gain at the expense of availability. The authors, however, consider that high availability is of first importance. If it is low the total possible gains by improvement in operating efficiency will suffer. This applies particularly where a group of stations are operated on a merit order of fuel cost. Gains in availability at the superior stations will be a double saving and will in some cases exceed the gains due to similar improvements in operating efficiency in the group.

Modifications to plant in order to give better availability may incidentally result in improved operating efficiency.

The relation may be investigated by:—

$$R = \text{Ratio } \frac{\text{Operating efficiency saving}}{\text{Availability saving}} = \frac{761{\cdot}6LC_f(Op_2 - Op_1)}{\eta DOp_1Op_2p(IC + F)} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where p = points improvement in availability.

Symbols are as before. Thus if $R < 1$ the availability saving predominates, and vice versa. Although each entity can be treated singly (to ascertain what conditions yield the maximum total gain), it is of value to identify the predominant gain.

(9) STANDARD MERIT

Maximum probable availability curves have been proposed in Fig. 8 for three groups of plant, based upon the actual results obtained in practice over the past 5 years.

The method of calculating the operating efficiency with allowances for running conditions has also been described. These are the two principal factors on which generating plant performance is judged. It would seem logical, therefore, to combine them into an overall factor of performance, and for the want of a better term the authors have called it "standard merit."

"Standard merit" is expressed in the following ratio:—

$$\frac{\text{Operating efficiency} \times \text{Actual availability}}{\text{Maximum probable availability}} = \frac{100A_a\eta_aH_t}{A_mXH_uK_{LF}} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where A_a = actual availability, %
A_m = maximum probable availability, % (Fig. 8)
η_a = actual thermal efficiency, % (after allowing for banking)
H_t = heat expended per kWh, B.Th.U. } Pearce
H_u = usable heat per lb of steam, B.Th.U. } Method
X = overall efficiency ratio, %
K_{LF} = load-factor correction, decimal. (Fig. 5)

Typical data used for this calculation are also provided in the nomogram, Fig. 10, referred to in the Appendix.

(10) CONCLUSIONS

(*a*) Pre-1930 plant should not be operated at above 45% average running plant load factor if good availability is to be consistently maintained.

(*b*) Marked improvements are to be noted in availability of the most recent plant installed since 1938 at 80% average running plant load factor.

(*c*) The lower breakdown rate per plant item of the pre-1930 group is notable when compared with that of the later plant groups.

(*d*) Good quality and grading of fuel supplies is needed, particularly for the pre-1930 plant, if maximum outputs are to be obtained.

(*e*) With larger units of plant, greater outputs between breakdowns have been possible, but it is not safe to conclude that larger units still would be to the general benefit of the supply industry. Size of unit required is related to the load curves and security needs.

(*f*) To obtain details of failures is not a straightforward matter at the present time. If they were systematically recorded and collected, afterwards to be openly discussed and/or published, it would be to the benefit of the electric supply industry.

(*g*) Maximum probable availability proposed for each class of plant is a useful guide to the performance that can be achieved. Until a wider field has been scrutinized, it is advocated that the curves submitted, which are representative of actual performance, should be adopted.

(*h*) Maximum probable efficiencies are determinable by the method described, and can be uniformly applied.

(*j*) Operating efficiencies made more prominent in station records would be to the benefit of all concerned. The figures should be obtained after due allowances have been made for varying running conditions. The authors consider that no adjustment other than for running plant load factor and banking coal, is worth considering, although most effects have been rigorously investigated.

(*k*) High availability of plant ranks first in importance, for it entails correspondingly greater total gains in operating efficiency.

(*l*) Overall performance of a station can be judged by reference to its availability and operating efficiency. It is suggested that the two factors be combined to give "standard merit." All classes of station alike will then get due recognition of their performances.

(*m*) High standard merit will be dependent mostly upon good administration, sound engineering practice and effective co-operation amongst all concerned.

(11) ACKNOWLEDGMENTS

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(13) APPENDIX—WORKED EXAMPLES AND NOMOGRAMS

(13.1) Examples

(13.1.1) Example 1 (Operating Efficiency). Three-Shift Base-Load Station.

Station A. Week ending Friday, 5th February, 1943.

Ideal efficiency for 300 lb/in², 800° F, 280° F feed-water temperature and 29·0 in vacuum = 39·5%.

Efficiency ratio for { 2–20 MW sets of 1929; 1–50 MW set of 1930; 1–50 MW set of 1938; weighted average commissioning date—1934 } = 63%

Maximum probable efficiency = 24·9%
at heat rate of 13 700 B.Th.U./kWh generated.

Running Hours.

20 MW for 134½ hours = 2 690 MWh
50 MW for 168 hours = 8 400 MWh
50 MW for 168 hours = 8 400 MWh

(*a*) Total plant MWh = 19 490
Units generated = 16 717 MWh

(*b*) Running plant load factor $= \frac{16\,717}{19\,490} = 85{\cdot}8\%$

(*c*) Load-factor correction = unity.

(*d*) Maximum probable efficiency at running plant load factor = 24·9% (heat rate 13 700)
Coal consumed 8 593 tons. Calorific value 12 520 B.Th.U./lb

(*e*) Estimated lb-hours of boilers banked = $7\,840 \times 10^3$

(*f*) Coal at 0·025 ton per 10 000 lb/hour = 20 tons

(*g*) Steaming coal = 8 593 − 20 = 8 573 tons

(*h*) Actual heat rate = 14 350 B.Th.U./kWh generated

(*i*) Operating efficiency $= \frac{13\,700}{14\,350} = 95{\cdot}47\%$

In this example the only allowance taken into account is the banking coal.

(13.1.2) Example 2. Two-Shift Peak-Load Station (March, 1943).

Station B. (Curtailed running.)
Basic heat rate 18 500 B.Th.U./kWh
Units generated for month 1 343 000
Coal consumed 1 467 tons
Hours on load 340 (105 load steps)

Turbines	Hours run	Units generated	Times run up
3 000 kW	8	13 000	1
5 000 kW	140	335 000	9
7 000 kW	275	995 000	26
= 2 649 000 kWh capacity.		1 343 000 = 50·7% load factor	

Boilers	Hours run	Hours banked	Raised from cold
40 000 lb/hr } 3·2 MW each	139	413	1
40 000 lb/hr } 3·2 MW each	48	113	0
40 000 lb/hr } 3·2 MW each	155	258	0
60 000 lb/hr 5 MW ..	252	338	2
20 000 lb/hr 2 MW ..	8	—	1
Banking allowance for above = 136·5 tons Total allowances = 162 tons			

True Loading Coal.

1 467 − 162 = 1 305 tons

Actual Operating Efficiency Heat Rate.

$$\frac{1\,305 \times 12\,500 \times 2\,240}{1\,343\,000} = 27\,208$$

Operating Efficiency.

$$\frac{\text{Basic heat rate adjusted}}{\text{Actual operating efficiency heat rate}} = \frac{20\,670}{27\,208} = 75{\cdot}97\%$$

All the allowances described except deterioration have been taken into consideration.

Had the operating efficiency been computed by the abbreviated method, the only figuring required would be:—

$$\frac{18\,500}{0{\cdot}895} = 20\,670 \text{ (correction for load factor)}$$

$$\frac{28^*(1\,467 - 136{\cdot}5)}{1{\cdot}343} = 27\,739 \text{ (actual net heat rate)}$$

$\frac{20\,670}{27\,739} = 74{\cdot}52$, i.e. only 1·45 points lower than by ultimate method, whilst avoiding all the calculations which serve only to inflate the allowances by 25·5 tons (136·5 tons allowed for banking only).

(13.2) Nomograms

(13.2.1) Relative Values of Availability and Operating Efficiency.

The nomogram, Fig. 9, will determine conditions under which the value of 1% gain in operating efficiency from 99 to 100% equals 1% gain in availability; e.g. when the coal price is 26s. per ton, load factor 57%, capital cost £20 per kW, overhead charges 13%, maximum probable efficiency 28%. Similarly when capital costs, overheads and maximum probable efficiency are unchanged, and when coal is 40s. per ton, the ratio will be unity only when the load factor is 36%. Further examples of the relationship between the two factors are shown by the position of the cursors, the sequential position of which will be self-explanatory.

The gain obtainable from 99 to 100% operating efficiency, as given by Fig. 9, supplies a datum from which other short-cut calculations may be made, thus:—

If it be required to assess the gain for any number of points from lower down the scale it is necessary to apply the following adjustment

$$Gop_1op_2 = G \times \frac{9\,900(op_2 - op_1)}{op_1op_2} \quad \ldots (6a)$$

where Gop_1op_2 = total gain in £ per annum per running MW by raising from op_1 to op_2.
G = gain in £ per annum per running MW by raising operating efficiency one point as per middle scale of nomogram.

* 28 is a coal constant when calorific value = 12 500.

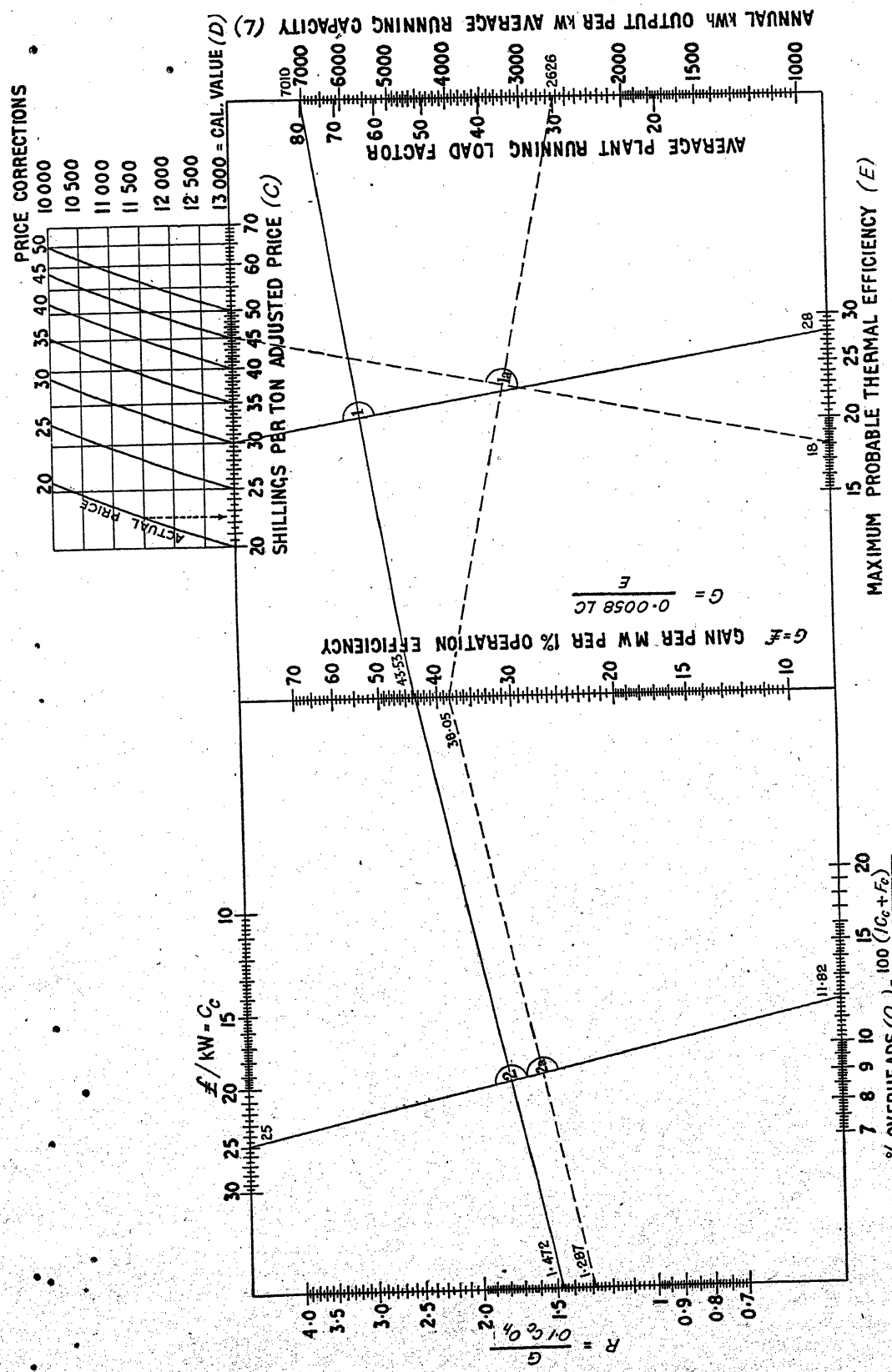


Fig. 9.—Relation of 1% increment of operating efficiencies to 1% increment of availability.

I = Capital charge expressed as decimal.
C_c = Capital cost, £ per kW.
F_o = Sum of fixed charges per kW for management, rates, insurance, salaries, wages, repairs and maintenance, oil, water and stores, £.

When $I = 7\%$ and $F_o = 24$s. per kW:—

Cap. cost, £/kW	16	17	18	19	20	21	22	23	24	25
Overheads, %	14·5	14·1	13·7	13·3	13	12·7	12·45	12·2	12·0	11·8

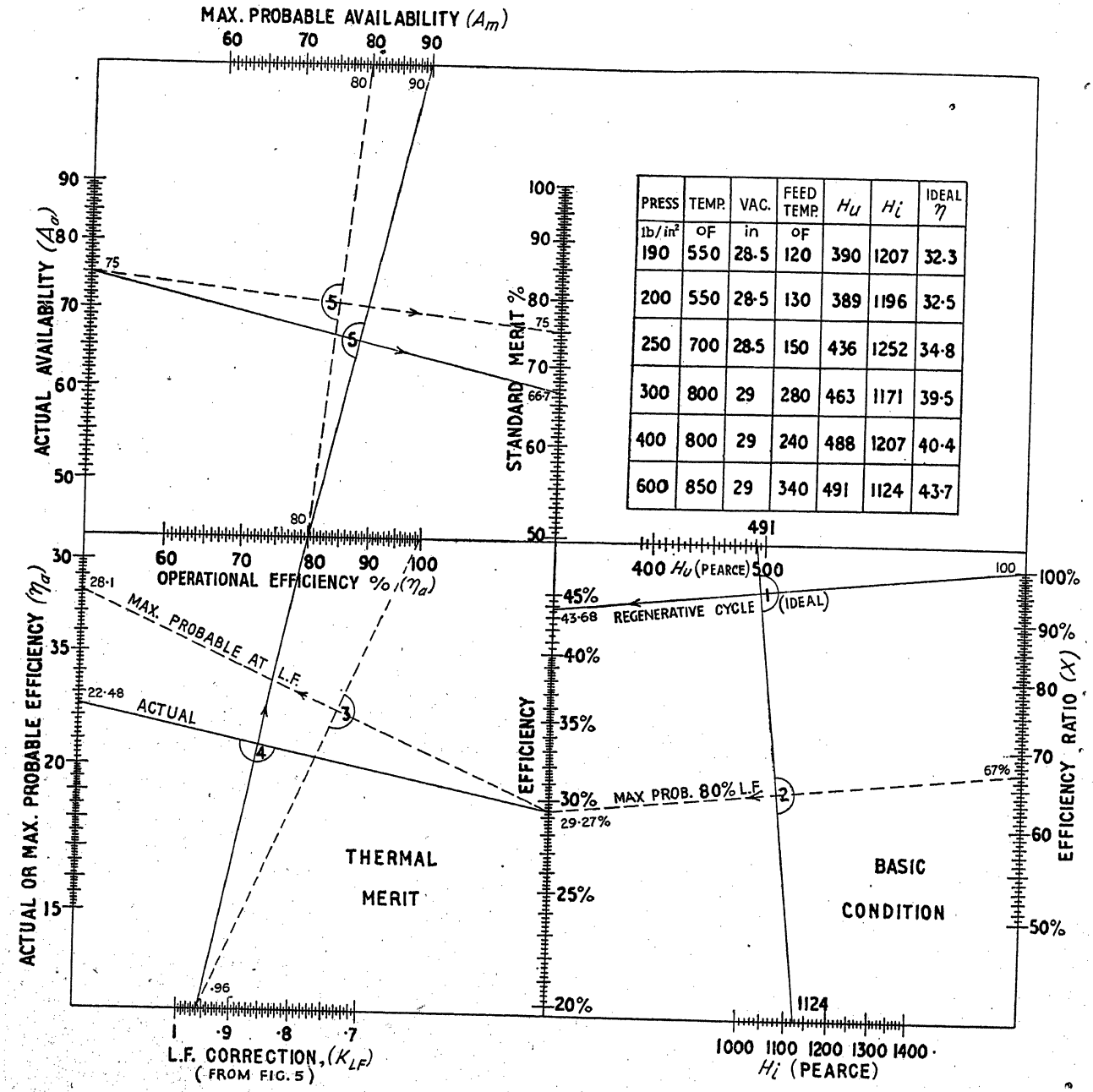


Fig. 10.—Nomogram for "standard merit" $= \frac{100 A_a \eta_u H_i}{A_m X H_u K_{LF}}$

op_1 = the lower operating efficiency.
op_2 = the higher operating efficiency.

Similar adjustments are needed for R in Fig. 9.

(13.2.2) **Nomogram for Standard Merit.**

Fig. 10 is a nomogram for the purpose of readily computing the standard merit of a station, and is largely self-explanatory. It provides for the calculation of operating efficiency from the ideal and maximum probable efficiencies, and allowances for load-factor correction. This, combined with the actual availability expressed as a percentage of the maximum probable availability, finally gives the standard merit.

The calculation can be identified by the sequence numbers entered in the semicircle on the cross hair-line cursor. E.g. No. 1 position gives the ideal efficiency obtainable from 600 lb/in² 850°/29 in vac., 340° F feed temperature, fixing H_u at 491 and H_i at 1 124: No. 2 position retains 491 and 1 124 as constants and corrects for 67% overall efficiency ratio, giving 29·27% as maximum probable efficiency at 80% load factor: No. 3 position corrects for lower load factors (first read from curves in Fig. 5) which, with 100% operation efficiency, gives 28·1% as maximum probable efficiency: No. 4 position retains 29·27% and 0·96, and, after intersecting at the actual efficiency, shows that the operating efficiency is 80% of the maximum probable: position 5 relates the figure last found (80%) to actual availability (75%) and maximum probable availability, indicating

(*a*) That the standard merit is 66·7% if the maximum probable availability is 90%, and

(*b*) That the standard merit is 75% if the maximum probable availability is 80%.

(13.3) **Formulae for Assessment of Thermal Gains in Terms of Operating Efficiency Points, and vice versa**

Equal increments of operating efficiency yield equal increments of thermal efficiency. The relationship of increment of operating efficiency to saving on fuel account, however, obeys the formula:—

Points gained

$$= Op_1\left(\frac{\text{Actual heat rate}}{\text{Actual heat rate} - \text{B.Th.U. saved per kWH}} - 1\right) \quad . \quad (7)$$

when Op_1 = the lower operating efficiency and the "B.Th.U. saved per kWh" determines the absolute saving.

If it be desired to find the B.Th.U. gained per kWh corresponding to any number of points, substitute the number of points for P in the formula

$$\text{Gain} = H_1\left(1 - \frac{Op_1}{Op_1 + P}\right) \quad . \quad . \quad . \quad . \quad (8)$$

where H_1 = heat rate under condition Op_1,
P = number of points increment in operating efficiency,
Op_1 = initial operating efficiency.

This formula holds good whether applied for small increments or for the total gains attributable to improving the operation efficiency from Op_1 to 100%.

To compare equal increments on the operating efficiency scale when these are on different parts of the scale, e.g. between Op_1 and Op_2 on the upper part, and Op_3 and Op_4 on the lower part (where $Op_2 - Op_1 = Op_4 - Op_3$)

the ratio

$$\frac{\text{upper gain}}{\text{lower gain}} = \frac{Op_3\, Op_4}{Op_1\, Op_2} \quad . \quad . \quad . \quad . \quad (9)$$

Although increments in points are equal the upper gain

$$= \frac{(Op_2 - Op_1)H_1}{Op_2} \text{ B.Th.U./kWh} \quad . \quad . \quad . \quad (10)$$

whilst the lower gain

$$= \frac{(Op_4 - Op_3)H_3}{Op_4} \text{ B.Th.U./kWh} \quad . \quad . \quad (10a)$$

where H_3 is the heat rate under condition Op_3.

The ratio (10)/(10a) leads to the more explicit ratio (9).

(13.4) **Example in the Calculation of G**

(*a*) Absolutely, by formula (2).
(*b*) By use of nomogram (Fig. 9).

A 60-MW station having a maximum probable efficiency of 25% raises its operating efficiency from 85% to 90%. The fuel cost is 35s. per ton, calorific value 12 500 B.Th.U./lb, running load factor 66·7%.

$$\text{By formula } G = \frac{60 \times 7\,616 \times 5\,843 \times 35 \times 5}{0{\cdot}25 \times 12\,500 \times 85 \times 90}$$

$$= £19\,545$$

By nomogram the datum gain = £49·5

$$G = \frac{49{\cdot}5 \times 60 \times 5 \times 9\,900}{85 \times 90} \text{ (see formula 6}a\text{)}$$

$$= £19\,200$$

The latter method merely applies multipliers for

(*a*) MW of plant (60)
(*b*) Number of points increment (90 − 85)
(*c*) Position of increment on the scale 9 900/(85 × 90)

and yields a result sufficiently near for practical purposes.

DISCUSSION BEFORE THE INSTITUTION, 3RD FEBRUARY, 1944

Mr. J. R. Beard: Papers have been read before The Institution describing new power stations or the design of power-station plant, but I think a paper such as this, dealing with operating performance from a statistical aspect, is a new departure. In the past there has been far too much tendency in this country to camouflage operating troubles, and far too little freedom in discussing and comparing operating methods and results. The benefits to be gained from a freer interchange of experience and views are very great, whether we are designers, manufacturers or operators.

The importance of these benefits to our national economy is also very marked. In 1938-39, the last year for which figures are available, the annual working cost of power generation for public supply in this country was £19·5 million, of which three-quarters was for coal. At the present time output is some 50 per cent greater while the cost of coal has practically doubled, so that station operators are now responsible for the efficient utilization of some £30 000 000 worth of coal. The capital invested in generating plant is some £200 millions, on which capital charges must be paid. Even slight improvements in efficiency of operation or in availability of plant therefore represent very large sums of money. I hope this paper will be the forerunner of many others of a similar kind.

I look upon the authors' proposals as only a first step in arriving at methods of sufficient accuracy to justify general use. They are, however, valuable in that they get down to fundamentals. This is most important if full advantage is to be taken from the competition engendered by published statistical comparisons. As an example, consider the Electricity Commissioners' comparison of the thermal efficiency of power stations. This arouses wide interest and has stimulated much competition between station operators which has been most helpful, but its weakness is that it stresses only one of the factors which enter into the attainment of lowest overall cost, this of course being the fundamental object of power generation. Its effect in increasing thermal efficiencies has been most marked and proves the great competitive value of published data. Such competition has, however, undoubtedly tended to encourage this increase without full regard for all the other factors affecting total cost, such as capital charges and availability. It needs, therefore, to be supplemented by comparative data relating to these other factors.

In dealing with operating efficiency, the authors make an interesting departure from the usual definition, i.e. the ratio of the actual thermal efficiency to the maximum possible thermal efficiency based on turbine and boiler guaranteed efficiencies. They make the denominator the *probable* thermal efficiency in order to eliminate losses of efficiency outside the control of the operators, and so to give a more direct measure of the efficiency of the operating staff. This has much in its favour. They appear, however, to have included steam-pipe losses and blow-down, blow-off and sundry leakages in their uncontrollable losses, which does not seem correct. It is also difficult to see why the magnitude of uncontrollable losses should be rigidly anchored to the year in which the plant was commissioned, as is done in Fig. 6. Surely the comparisons are also vitiated by variation in coal quality.

My main criticism is of the part dealing with availability, where the authors' views are most controversial, especially their suggestion in Section 7.8 that when the kW capacity of the boiler plant is greater than that of the turbine plant in a station, or vice versa, the availability should be calculated on the basis of the higher kW capacity of the two.

It is a curious argument that those stations in which extra capital has been invested in spare boiler-plant should be deprived of the advantage of, or credit for, the extra availability which has thus been obtained. The authors appear to take the line that the ideal is for the maximum kW capacities of the boiler plant and the turbine plant to be the same. This may become possible in the future, but for the present it must be accepted that boiler availability cannot be equal to turbine availability. Therefore, it is desirable to make the kW capacity of the boiler plant greater than that of the turbine plant; a spare boiler in six, for example, is a profitable form of investment because it improves the average available capacity of the plant as a whole. It will be noticed in Table 1 that in Group C, consisting of plant installed since 1938, the total turbine capacity is 277·5 MW, while the total boiler capacity is only 246 MW on the reasonable assumption of 10 lb of steam per hour per kW. I suggest that this under-boilering of the recent stations is possibly one of the reasons why the average available plant capacity shown in Fig. 1 has not increased since 1940. Incidentally the authors say that this fact prompted them to make a study of operation records, but I cannot find any direct explanation in the paper of why the average available capacity did not increase during those years.

I was puzzled by equation (1) in Section 7.8. Presumably $C_{a.m.}$ and $C_{p.m.}$ are not the average capacities available, but the sum of the average daily capacities for the period under consideration. The authors appear to consider availability on a yearly basis, but this is misleading and it should be based on the three winter months when the plant capacity is really needed; if so, one would aim at a higher maximum figure than 90 per cent. This can be obtained if maintenance programmes are properly spread over a period of lower demand.

I view with considerable misgiving the authors' proposed "standard merit." It seems to be a very artificial product of two entirely separate matters. I agree that enough attention is not paid to availability, but I would prefer to see this done by keeping parallel records of operating efficiency and availability, rather than by any attempt at an all-embracing figure.

Mr. J. D. Peattie: In their own area the authors have already been successful in stimulating interest in generating-station efficiency and availability. This paper will be well worth while if it arouses enthusiasm over a still wider area.

They review the records of a fraction of the generating plant operating under the direction of the C.E.B. This fraction, less than one-tenth, is not necessarily a fully representative sample of the whole, and care must be exercised in drawing general conclusions from the results quoted in the paper.

The authors' conclusions on quality and suitability of coal are certainly of general application. During the last few years generating station engineers have had to face greatly-increased difficulties due to poor and varying quality of coal supplied. On the whole, engineers have been particularly successful in agreeing standard specifications with their suppliers for raw materials and finished products. This co-operation ensures the most economical use of the materials and labour to give a specified service. In view of the magnitude of the national coal bill for public electricity supply, it is incumbent on engineers responsible for generating stations to specify their requirements accurately and to insist, as a contractual obligation, on fuel being supplied in accordance with specification.

The Electricity Commissioners' fuel returns have been of the greatest value in focusing attention on thermal efficiency, particularly of the best stations. The average stations have, however, not attracted the same attention. While the best stations set a standard for the remainder, the need has long been felt for a fairer basis of comparison which might be applied more generally.

By using an ideal standard efficiency based on the steam cycle and making arbitrary allowances for various operating conditions, the authors arrive at a single figure for what they call "operating efficiency." In effect, it is a modification of the efficiency ratio long used in connection with the Rankine cycle for steam engines, but applied to the complete station. It is very convenient to simplify the problem in this way and arrive at a single figure for purposes of comparison, but the term "operating efficiency" seems hardly appropriate. It appears that certain of the results in Fig. 7 are due to causes quite outside the control of the operating staff, depending on the design of the station as a whole or of some particular part of the plant. In any case, the figure itself only becomes valuable when it results in action to improve performance. I fully agree with the authors' statement that "correct analysis of the causes of the deficiency is the first step to better performance." Their suggestions for such analysis, in Table 5, are worth close study.

I find it difficult to follow the authors' suggestions for the use of standard merit as a simple product of two percentages: efficiency and availability. There are other important factors to be considered when assessing the relative merits of stations. Even if it were desirable to express relative merit by a single percentage, due weight would have to be given to each of these factors. Simple multiplication or addition is not sufficient.

Some of the authors' arguments might be taken to support the view that availability and efficiency can be achieved only by extra capital expenditure, or that availability can be obtained only at the expense of efficiency. In my opinion, both availability and efficiency are much more dependent on skill in design, construction, and operation, than on mere expenditure of labour and material.

Mr. C. G. Carrothers: Fig. 3 shows that the majority of shutdowns are of less than one day's duration and only rarely exceed four days. Tidal schemes, which are now receiving so much attention, would therefore be of great assistance to the practical operation of steam plant, because the average availability of tidal peak power in the course of a year would consist of 28 periods of three consecutive days, 12 of which would either include or be contiguous to Sundays. During these periods a considerable amount of maintenance work could be carried out, and a large number of incipient faults could be anticipated. It would be interesting if the authors would give their assessment of the effect of the above relief periods on the availability of steam stations interconnected with the tidal scheme, and also their estimate of the effect of tidal power supplied during off-peak periods.

For the basic thermal efficiency, the authors make use of a feed-heating cycle arranged in stages of 50°F so that the number of stages is pre-arranged for any given final feed-water temperature. For high feed-water temperatures the increments of heating may be as much as 75°F, and this figure has been used in American practice to control the cost of equipment. In this connection, attention might be drawn to a method of calculating theoretical thermal efficiency, given in a recent paper, which takes into account the actual number of feed-heating stages.* It enables the required result to be arrived at by means of standard heat-drop tables and the application of corrections, the magnitude of which is graphically presented in the paper.

The efficiencies derived by the authors' method, and given in Fig. 10, are almost identical with the corresponding efficiencies derived from the Field cycle to which the authors refer. I suggest that a simple approach to reality could be made using the Field formula in the first instance, and applying corrections as necessary in respect of the actual number of feed-heating stages. Do the authors consider that a third correction curve corresponding to their Figs. 5 and 6 could be devised to meet this requirement?

* H. S. HORSMAN: *Proceedings of the Institution of Mechanical Engineers*, 1941, 146, p. 5.

Failing this the only basis which provides for the number of feed-heating stages is the paper referred to.

In Table 5 an analysis is made of the uncontrollable sources of inefficiency in combustion. It is a very interesting comment on the closeness of design of boiler equipment that more direct reference is not made by the authors to excess air as a source of low combustion efficiency. Do the authors think that in the present stage of development of the design and operation of steam-generating plant it is unnecessary to underline the desirability of avoiding excess air, or do they consider that the quest of high CO_2 may result in high combustion efficiency at the expense of heavy maintenance of stokers and settings?

Mr. H. V. Pugh: Being connected with one of the stations under review in the paper, I can confirm that much success has been obtained in the area by the methods described. The authors and those associated with them have had to deal with a large number of small, but geographically important, stations, for in the area concerned there are only three power stations with an installed capacity of over 100 MW. Table 1 includes no fewer than 48 generating units of 7·5-MW capacity or less. The authors' aim was to produce a method of comparison which would enable the operators in smaller stations to compare their results with those achieved in the bigger modern stations.

In Section 3 they point out that the quality of coal has deteriorated. Last month, for instance, in one station about 47 000 tons of coal were burnt and these consisted of 47 different varieties. The ash content varied from about 9% to 28%, and the volatiles from 10% to 21%.

On the question of availability, with boilers first put into commission—four in 1925 and four in 1927, comprising 60 000 lb/hr units served by three grates—we have obtained availabilities for the last three years—1941 to 1943—of 91·15%, 90·98% and 89·65% respectively. At the same time, with a more modern design of pulverized-fuel-fired boilers of 182 000-lb/hr capacity, it has been possible during the same years to keep up an average availability of more than 92%. While design has a great influence on the availability and the efficiency of plant, much credit is due to the power-station staffs when both good availability and high efficiency are obtained even with new plant.

The authors refer in Section 7 to skilled supervision. We must change our ideas about recruiting power-station staffs, and utilizing their services after years on shift work. When a charge engineer reaches the age of 50 he should be taken off shift, and his knowledge and experience used with considerable advantage to the proper maintenance of plant, by putting him on special studies of lubrication, water treatment and other items which require closer supervision than they at present receive.

A shift charge engineer in any of our stations may, with his colleagues, be responsible for the efficient combustion of over 500 000 tons of coal per annum; and everything should be done to keep these men fresh and keen at their work, particularly by promotion, so that full scope can be given to the young men in the power stations before years of shift work kills their enthusiasm.

We will have to stop using such terms as "turbine driver" and "stoker." The man who controls a modern pulverized-fuel boiler is something more than a stoker, and in recognition of this fact he should train men for plant-operating duties who have at least had some secondary school education.

Mr. S. M. Hill: There are several points I would like to raise. One is the difference in availability between the turbines and the boilers. It is not exceptional for a turbine to have an availability of 90–95%, whereas a boiler does not approach anywhere near that figure except in a few cases, the availability being generally 80–85%.

From Table 1 it is very evident that the amount of excess steam over the turbine consumption is very small. In Group A it is approximately 9·7%, in Group B 16%, and in Group C practically nothing. This does not seem to give proper opportunity for adequate maintenance. I think it is accepted that lack of output of stations is generally due to lack of boiler plant; in other words, most stations are running on boiler maximum.

Fig. 2 gives a proportion of 18% fines in coal deliveries in 1942. My experience is that this figure to-day is more in the region of 50%. This high proportion is having a very bad effect. The wear on fan runners, for instance, has increased about five times. Fans which used to last ten years now wear out in two. Another feature affecting availability is the supply of coal of different characteristics. Instead of sending all the 57 varieties, mentioned by a previous speaker, to all the plants, why not send one variety to each? It may sound a little Utopian, but I think that the situation could partly be met on those lines, for the fewer classes of coal a station has to burn the better.

Is the "standard merit" a good thing? Have the authors made out a good case for its adoption? I think they have. The pre-war yard-stick of station performance was the thermal efficiency figures published in the returns of the Electricity Commissioners. These figures were of considerable interest, but mainly to the first half-dozen stations and were not encouraging to the older stations.

Any method of comparison which takes into account factors over which the operating staff has no control, is good; but the staffs in the various stations being compared must be convinced that they are getting a fair deal, otherwise no lasting improvement will be achieved. The system should therefore take into account as many factors as possible. With this object in view, I hope the authors will expand their system as time goes on, if they can do so without undue complication.

Mr. A. R. Cooper: The authors, for about the first time in public, are putting a cash value on the unsuitability of coal. In their case, for an area covering about 10 per cent of the total C.E.B. plant in the country, the net effect of unsuitable fuels is to nullify a capital expenditure of about £1 500 000, while in addition the coal industry has to provide still more fuel to meet the demand from the electricity-supply industry.

It is useful to remember that increasing the load factor on a generating station usually raises its thermal efficiency, but increasing the load factor on an interconnected system, such as a C.E.B. area, usually reduces the thermal efficiency, because the less-efficient plants become more heavily loaded. This fact is not always appreciated when extolling the benefits of high load factor.

Table 5 is particularly interesting, and gives a method of presentation which should be of considerable value to station staffs. The method of splitting up what happens to the heat which has cost so much is most illuminating, and if this subject is tackled with enthusiasm the average station engineer will soon be able to locate the causes of any reduction in thermal efficiency.

Care must be taken in drawing conclusions from Fig. 8. The inference to be drawn from the curves is that one can expect a better overall economic performance from modern plant than from older plant; and the facts collected by the authors support that general conclusion. But there is much evidence to show that this is not a safe generalization for the country as a whole. Figures for some 2 000 000 kW of sets and boilers taken over a 3-year period show that with boilers varying from 100 000 to 300 000 lb/hr capacity the four top places on the availability list are occupied by groups of boilers varying from 8 to 10½ years old, and the four bottom places by groups 3 to 5 years old. On turbines up to 75 MW, the top three places are held by machines varying from 11 to 14 years old, and the bottom three places by machines from 3½ to 5½ years old. The conclusion reached from an examination of Fig. 8 is that progress is in general on the right lines; the conclusion indicated by my figures is that some radical change in design, manufacture or operating tech-

nique is urgently required. I do not suggest that my figures are conclusive for the country as a whole, but they do indicate that the problem needs to be approached in its broadest aspects.

Regarding standard merit, there are many difficulties in comparing the relative performance of stations by the proposed method. When full account has been taken of all the variables connected with the operation of a station, the comparison becomes essentially one of the quality of performance of the operating personnel of the stations. It would therefore seem reasonable to take some account of the numbers of the personnel engaged in producing higher availability, and probably also of the remuneration paid to those responsible for producing it.

Mr. R. A. W. Connor: I feel that this paper, together with others recently presented to The Institution, reveals the necessity for more published data regarding plant availability and operation; also that the time is now ripe for formulating a standard code of practice for evaluating the performance of stations.

Fig. 5 shows the correction for load factor varying consistently with size of station whose turbine capacity varies from 5 to 50 MW. Fig. A shows the operation efficiency determined by

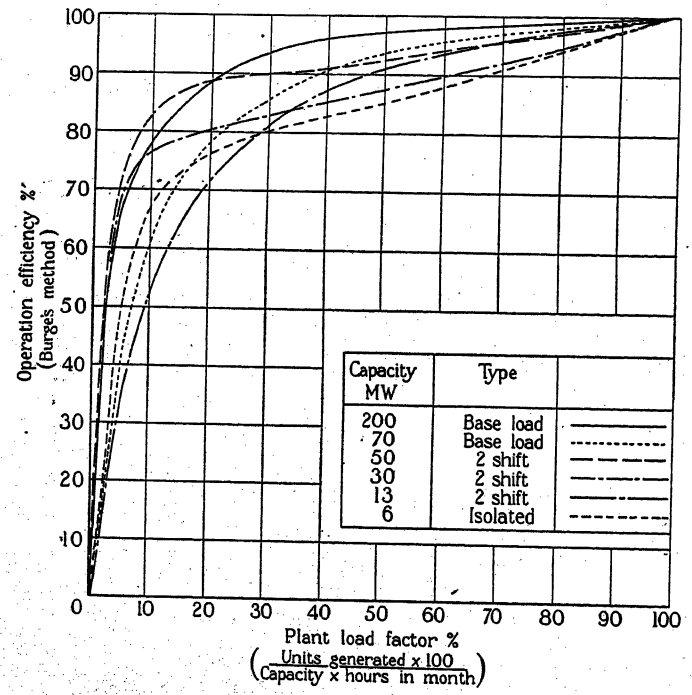


Fig. A

the method suggested by Mr. W. S. Burge compared with the plant load factors for six different stations. These curves support the view that there is no fixed relationship between load factor and operating efficiency. Again, in the secondary stations in particular 80% is not necessarily the most economic load factor.

The modern tendency is to use the output thermal efficiency for all purposes, which has many advantages. The authors have, however, based their calculations on units generated as shown in the correction curve Fig. 6. The Commissioners' returns now base all figures on units output, and it would apparently have been possible to make an allowance for this in the pre-1930 period when efficiencies were calculated on units generated. By using the authors' method the allowance for power-station auxiliaries is entirely ignored; I think this is a mistake.

With regard to the merit factor, I agree with previous speakers that it is rather unorthodox to multiply plant efficiency by availability, but there does not appear to be any alternative. In my opinion, the performance of a station can be expressed to the best advantage on the lines originally suggested by W. S. Burge. In addition a multiplying factor to allow for plant availability can be added as suggested by the authors; the complete statement would then be—

$$\text{Factor of merit} = \frac{\text{Availability} \times \text{Actual overall output thermal efficiency}}{\text{Cycle efficiency} \times \text{Optimum plant item efficiency}}.$$

It is very important that the complete equation should be stated in referring to the performance of a particular station.

Mr. E. T. G. Emery: In calculating the maximum probable efficiency in Section 7.1, the authors include vacuum as one of the factors to be taken into account. If the object of the proposed calculations is to assess the effects of poor operation, surely the fouling of condensers should be considered? I suggest, therefore, that circulating-water temperature be substituted for vacuum. Since we are dealing with an ideal machine, we can assume no temperature difference to exist between circulating-water temperature and condensate, so that the vacuum would always correspond exactly to a condensate temperature equal to the circulating-water temperature. As the ideal efficiency depends upon circulating-water temperature, it is essential that this be calculated specially for each case, using the true circulating-water temperature recorded; otherwise the operating efficiency would show a seasonal fluctuation.

In all the published methods of calculating maximum probable efficiency one of the *given* quantities is the final feed-water temperature. In an actual machine, this temperature varies with the plant load factor, and, if the final feed temperature is to be taken as a terminal condition, the ideal efficiency also varies with the plant load factor, which is another reason why the maximum probable efficiency must be calculated in each case. In fact, the final feed temperature is not a terminal condition *applied to* the turbine; it *results from* the turbine, and the value accruing from the operation of an ideal machine would be the optimum value corresponding to the number of heaters. Can the authors suggest any practical method of determining this optimum temperature, because if we can establish its value it can be used as a constant in the calculations, irrespective of the final feed temperature actually produced?

Station load factor is not mentioned as a factor affecting efficiency, but from Section 10 (*j*), it would appear that this has been investigated and found to have no appreciable effect. If this is so, an important issue is raised as a great deal of costing is carried out with the formulae in S.R. & O. 1015 in which station load factor occupies an important position.

Referring to Fig. 5, it can be shown that if the Willans line of heat consumption against load is straight, as the authors have assumed, then the correction factor is given by $(80r/L + 1 - r)^{-1}$ where r is the ratio of heat consumption at no load to the heat consumption at 80% plant load factor. Comparing this with the authors' formula: $r = (1 + 80K/F)^{-1}$, they have used values of r ranging from 20·7% at 5 MW to 9·5% at 50 MW. I suggest that there is no point in obscuring the value of r, and that the formula is best stated in the form I have given.

If the work involved in carrying out the authors' proposals will bring about improved operation by way of efficiency and availability, then the labour may be worth while; but the methods proposed seem to have so many approximations that I wonder whether there is not some simpler and more reliable method of getting at the desired result. I suggest as a possible line of investigation the principles of quality control as applied to the more tangible manufactured products.

Mr. E. McCabe: That the authors' method of determining operating efficiency provides a sound basis for the measurement of a somewhat nebulous quantity is shown by the placing of the

generating stations concerned in the "merit list." In this list stations of similar size, characteristics and target efficiencies do not tend to fall into groups, but are well distributed among dissimilar stations. It is, I believe, generally agreed between the engineers responsible for the plants so far participating in the scheme, that interest in economic operation has been stimulated by it, and that in fact the operating-efficiency figures derived by the authors' methods reflect with a certain degree of fidelity the information which they are intended to convey.

The operating-efficiency figure shares with the thermal-efficiency figure the disadvantage of being in all probability less accurate than its least accurate factor. It may well be said that inaccuracies will be included, but one of the major sources of inaccuracy is one which is by no means new, and is accepted as inevitable by many generating-station engineers in producing their normal performance statistics. I refer to the errors which can arise in arriving at the fundamental factor of heat input, in which careless sampling of some grades of coal leads to errors of 2–5% in the final result. Moisture determinations may be equally inaccurate, and careful laboratory work may lose most of its value. A practice exists at some stations of basing station performance on coal weights determined at the colliery, which may be appreciably different from the weight actually fed to the boilers. This not only results in a regrettable separation of the points of weighing and sampling, but also includes in the station engineer's results a factor depending on climatic conditions and on the ability or willingness of the appropriate persons to keep rolling stock in repair. Much of the value of the standards proposed by the authors may be lost, unless efforts are made to produce reliable and accurate data on which to base the calculations.

I do not understand the doubts which beset some of the previous speakers regarding the practice of multiplying together two not-directly related percentages. Most of them probably do not hesitate to multiply the very much more widely differing component parts of that very useful unit, the man-hour!

Mr. G. F. Kennedy (*communicated*): The authors have derived some very valuable facts from a mass of statistical information collected during years which have been most difficult ones from the point of view of power-station operating engineers. An increasing amount of attention has recently been focused on the necessity for ensuring a high availability factor at all power stations, and I should like the authors' comments on the suggestion that the troubles experienced with the more recent generating plant included under Group C could have been avoided had more attention been paid in the design stage to availability than to a high overall thermal efficiency.

Can the authors say whether in their experience powdered-fuel plants have, in general, given a higher availability than stoker-operated plants? From the design point of view, it is generally considered that this should be the case, and that the higher availability of powdered fuel plants should to some extent compensate for their higher capital cost.

There appears to be no reference to the importance of an established routine for the inspection and maintenance of each item of generating-station plant. Are the stations in which all items of plant are regularly inspected, and the results systematically logged, given a higher availability than those in which this work does not receive such careful attention?

The authors have produced a yard-stick by which the performance of power stations may be judged. I would, however, criticize the suggestion that the standard merit should be based on the higher kilowatt capacity where stations are over-boilered. The authors have shown that under normal working conditions it is not at present practicable to expect such a high availability from the boilers as from the turbine plant in any station. Present conditions cannot be described as normal, and the irregular quality of coal supplied, coupled with the frequent necessity for running boilers at or near their rated output, must inevitably reduce still further their relative availability. In such circumstances, undertakings which install excess boiler capacity would appear to be absolutely justified, and it seems a pity that the standard merit of their stations should thus be adversely affected.

In this connection it is interesting to note that if it is assumed in Table 1 that the weighted average steam consumption for the turbine plant included in Group A is 11·0 lb/kWh, the excess of boiler capacity over turbine capacity is only 5%. In Group B, if the weighted average is assumed as 10 lb/kWh, the excess is 16%, and in Group C, with a weighted average of 9·2 lb/kWh, there is actually a shortage of boiler plant of some 3½%.

Mr. C. W. Priest (*communicated*): I was very interested in the analysis of breakdowns and availability given in the paper. The burden of unsuitable fuels is given as 10–15% loss of availability on the total plant installed, a burden which must be increased by additional maintenance charges, extra tonnage and extra labour requirements at a time of greatest shortage. Table 2 appears to indicate that the more modern plant in Group C is more susceptible to breakdown or outage than the intermediate plant in Group B, whilst the latter is, in turn, more susceptible than the oldest plant in Group A. It will be noticed that the increased rate of breakdown per plant item is not confined to the steam-generating plant, but is also apparent in governors, oil systems and condensers. The size of the plant items in Group C is presumably larger than in the other groups, so that an increased outage of the latest and largest units would be very serious. Perhaps the authors would comment on this point.

Statistical comparison of station performance, even in the simple form of thermal efficiency, has, I believe, had a marked and beneficial effect within the industry. I am all in favour of maintaining such a comparison, and I believe the system advocated by the authors is a definite advance on the present thermal-efficiency basis. It merits a try-out on a still larger scale.

There is one point, not brought out in the paper, upon which I should like the authors' views. All figures of station performance are ultimately based on tons of fuel and heat value, and for all official statistics it is at present necessary to equate the tons burned with the tons paid for, whilst the calorific value used must be the heat content of the coal as received. With these figures all losses in heaps are debited to station performance. If fuel is purchased on the colliery advised weights, then station performance must also bear the burden of loss in transit. It seems to me that such losses might be separated, and carried as a cost item, leaving the technical efficiency to be calculated on the basis of fuel to boiler hopper, excluding all prior losses.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. R. W. Biles and G. W. Maxfield (*in reply*): We fully agree with Mr. Beard's opening remarks, particularly his reference to the need of other factors, such as capital charges, availability, etc., of power station performance being recorded for purposes of comparison. He is thinking on different lines, however, when referring to operating efficiency. Mr. Peattie suggests that the term is hardly appropriate. Our denominator is the maximum possible thermal efficiency based on turbine and boiler guaranteed efficiency at the running plant load factor. No other allowances for uncontrollable losses included in this item were made. The term "operating efficiency" is regarded in its widest sense and is a measure of the manipulation of the station's operators,

of design performance, manufacturing quality and station management.

With "availability" we have endeavoured to find a formula which would give fair calculations for all stations. Over-boilered stations have the advantage over the balanced and under-boilered stations since cleaning and repairs can be done without loss of effective capacity and therefore of availability. There seems to be no justifiable rule for all classes of stations to be provided with spare boiler capacity. Base-load stations with high annual average running plant load factors would have the best claim. Mr. Pugh refers to high availabilities achieved with balanced plant, i.e. without spare boiler capacity. Since boiler availability does not generally equal turbine availability, we are inclined to base the calculation on effective station capacity, which may be limited by turbines or boilers. This is a considerable advantage to some stations with spare boiler capacity equal to 1 in 4.

We gave no direct explanation in the paper as to why the availability did not increase from 1940–1942. A study of the breakdown analysis shows the big rise in breakdowns, and therefore loss in availability, with an appreciable rise in running plant load factor. Calculation of availability based on three winter months instead of yearly would be unfair, particularly to the base-load stations which are needed to operate fully loaded throughout the year. Furthermore, the spring and autumn loads are becoming the most difficult to meet.

We value operating efficiency and availability points as of equal merit, although their monetary values may be different. We agree that parallel records should be kept and, as an alternative, we have no objection to the mean value of the two factors to represent "standard merit." We have had some difficulty in finding an alternative term for "operating efficiency." We agree with Mr. Peattie that extra capital expenditure to gain improved availability and/or operating efficiency should not be resorted to until all other means have been tried and have failed.

We cannot see that tidal schemes, as suggested by Mr. Carrothers, will be of much assistance with shutdowns, since they will not always occur when tidal power is available and, furthermore, only minor maintenance can be done at steam stations at times when tidal power is at its peak. Much depends upon the type of tidal-power scheme.

Several alternatives for calculating the basic thermal efficiency have been tried, with little difference in the result. The one adopted is a practical and convenient calculation. Mr. Carrothers' suggested alternative will be considered.

Mr. Pugh's figures of availability are a demonstration of what can be achieved with old and modern plant by good management, and enthusiastic, efficient and well-organized staffs. We endorse his comments regarding the quality and training of power station staffs.

Mr. Cooper has drawn attention to the diversity of results in availability, and supports a country-wide survey. Fig. 8 is derived from the best performances and the curves are set up as a standard. Station performances which fall short of those standards should be carefully analysed to find the cause.

The effect of load factor on thermal efficiency in an interconnected system is often similar to that for an individual station when two or more pressures are used. Table 4 was devised to cater for two pressures; similarly in Fig. 5 adjustment for machine-hours automatically lowers the maximum possible efficiency for the added use of older plant, giving also an incentive to efficient loading of plant within the station when all plant is available. Standard merit is determined from basic technical facts irrespective of the numbers of personnel engaged; these could be taken into account, if desired, in the final analysis.

We agree with Mr. Connor that there is no fixed relationship between operating efficiency and load factor. According to our definition, operating efficiency will vary considerably for various reasons not connected with load factor. The adoption of output efficiencies or "sent out" figures appears to complicate the calculations. It is appreciated that auxiliary power requirements vary between stations, and that in modern plant there is a tendency for them to rise.

In reply to Mr. Emery, the designed vacuum is adopted for the calculation, and any deviation from it due to fouling of consensers is the responsibility of the operating staff and should appear in the analysis of "accountables." We appreciate that the "ideal efficiency" will vary with circulating water temperature, and seasonal variations will be met with, but all stations alike will be affected in some degree, and in a comparison over a 12-month period we think they can be ignored. In the methods proposed, small discrepancies have been ignored so as to arrive at a simplified practical method applicable to a complex problem. The discrepancies will generally be common to all station results if the system is uniformly applied, and none will suffer. We would welcome suggestions, fully explored, of a simpler approach to the problem.

Mr. Emery may have misinterpreted Section 10(*j*), as this definitely states that the efficiency must be expected to droop with load factor. In Fig. 5, the general approach was similar to that given by Mr. Emery's first formula. F in the subsidiary table corresponds to r in Mr. Emery's formula, except that it is related to 100% instead of 80% load.

In reply to Mr. Kennedy, Group C plant was installed as base plant with the full knowledge of designers and manufacturers, i.e. to operate continuously at high load factors. Margins in design were presumably incorporated to give good availability, although they were not successful in every case. In some cases pulverized-fuel plants, although not always higher in capital cost, have given higher availability than stoker-operated plant.

We agree with Mr. Priest's observations on the extra burden of unsuitable fuels and the greater breakdown rate of Group C compared with the other groups. We welcome his support for trying out the system on a wider scale.

TRANSMISSION AND DISTRIBUTION OF ELECTRICITY TO MINES*

By B. L. METCALF, Member.†

(*The paper was first received* 1*st November*, 1943, *and in revised form* 1*st January*, 1944. *It was read before the* TRANSMISSION SECTION 9*th February, and before the* WESTERN CENTRE 13*th March*, 1944.)

SUMMARY

With the more general recognition of the advantages and economies to be obtained by the electrification of the surface plant and, where mining conditions permit, the underground machinery at collieries, there is likely to be a big increase in the consumption of electricity in the mining industry after the war. In the South Wales coalfield, where approximately 16% of the total output of the United Kingdom is raised, the transmission and distribution of electricity introduces special problems owing to the hilly nature of the country. To enable some idea of the potential demand at collieries to be obtained, the load for a typical group of collieries is analysed. Some notes are included on the choice of switchgear for collieries and on the influence on this choice of the proposed amendments to the Regulations for the Use of Electricity in Mines.

Information is given regarding the damage to transmission towers during the ice storm of 1940, and a proposal is made to amend the Regulations of the Electricity Commissioners governing ice-loading for conductors. A new design of cross-arm for a single-circuit 33-kV overhead line is illustrated. Recommendations are made for the standardization of equipment required for the electrification of collieries.

(1) INTRODUCTION

The degree of colliery electrification varies throughout the country, and each coalfield has certain special conditions to face. In South Wales most of the special problems are imposed by the concentration of the collieries in narrow valleys and the hilly nature of the country which must be crossed by the transmission lines supplying the collieries. The large demands for compressed air and for pumping also increase the power requirements and call for the transmission and distribution of fairly large blocks of power.

A number of the larger colliery companies throughout the country generate some of their electric power, but this is frequently done in small units and, owing to amalgamations and the growth of loads, these units are inadequate to meet the total demand, and the units themselves are often inefficient. Very few satisfactory arrangements have been made for working colliery generating plant in parallel with the Grid or with power companies' systems, and the colliery electrical load, which is continually increasing, has not been properly co-ordinated with the other industrial electrical loads in the same area. Colliery generating and transmission systems are for the most part quite independent entities, and as the collieries in one area become organized in larger groups the tendency is to spread the colliery transmission system over an even wider field, duplicating, in some instances, existing transmission lines. On the other hand collieries can usefully generate electricity as a by-product of their normal business, and their potential contribution to the generating capacity of an industrial area must be taken into account.

Continuity of supply is of vital importance to collieries, and for this reason alone they are justified in retaining a reasonable capacity of generating plant at the pit-head to maintain essential plant in the event of some major trouble interrupting the supplies from outside, and there is no reason why this generating plant should not be efficient and well maintained.

To accelerate the electrification of colliery surface plant, rigid standardization of the different units of equipment in use and in the application of certain of the regulations governing the transmission, distribution and use of electricity is recommended.

(2) POTENTIAL DEMAND FROM THE SOUTH WALES COALFIELD FOR ELECTRICITY

In the years 1934 and 1935 the output of coal from the South Wales coalfield was just over 35 million tons, or 15·8% of the total output for the United Kingdom. Of this approximately 5 million tons was anthracite, leaving 30 million tons of bituminous coal. In the following discussion the anthracite collieries are not taken into account as their power requirements are different from those at the bituminous coal pits. Moreover, the information given with regard to the latter can be applied, with certain simple modifications to suit local conditions, to other coalfields in Great Britain.

In the South Wales coalfield there are two main factors which tend to increase the power consumption per ton of coal raised relative to other areas, namely the heavy pumping load and the extensive use of compressed air. This increase in power consumption is offset to a certain extent by the shallower shafts in the South Wales mines, compared with the deeper shafts in Yorkshire, Lancashire and the Midlands, where the consumption of the winders is higher.

Where mining conditions do not allow the use of electricity in the area within 300 yards of the coal face, compressed air must be used for coal cutting, conveying, drilling, pumping and hauling. This means that four or five times the power must be generated on the surface for these compressed-air drives, compared with the power required for direct electric drive. In South Wales, owing to the almost universal availability of compressed air on the coal face, extensive use is made of air picks in place of coal cutters.

A fair average figure for the power consumption in the South Wales steam and bituminous coal mines is 35 kWh per ton, assuming the power for washeries to be included. If all the collieries in the area under consideration were completely electrified, including electrically-driven compressors, winders, fans, etc., the total annual consumption would be 1 050 million kWh. At an average load factor of 45% this represents a maximum demand of approximately 270 000 kW.

(3) ESTIMATED ENERGY CONSUMPTION

The steam and bituminous coalfield of South Wales is approximately 28 miles by 18 miles, or 500 square miles. In this survey of the power requirements of the coalfield no other industrial loads have been considered, although these are considerable. They would be further increased if railway and road electrification up the valleys were included as well, and in any regional scheme for developing the area the power required for railway and trolleybus electrification should not be left out of account.

The potential maximum demand from the coal industry of South Wales alone, if completely electrified, is approximately 600 kW per square mile. If further underground electrification is carried out at the expense of compressed air this figure will, of

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* Transmission Section paper.

course, be reduced. The law of diminishing returns would offset this to a certain extent as coal has continually to be conveyed and hauled greater distances, and there is still a fair amount of natural horse-power in use which will eventually be mechanized. Fig. 1 shows the concentration of the coal industry in the area, based on the number of men employed in 1937, the size of the squares being proportional to the number of men working at that date in the locality in which the squares are drawn.

(3.1) For South Wales

With modern generating plant it is possible to deliver 1 kWh of electricity to the colliery 3·3-kV busbars for a consumption of 1·5 lb of coal at the power station, or a total consumption of 703 000 tons/annum for 30 million tons of coal raised. This represents a coal consumption of 2·35% of the coal raised. If the consumption were 45 kWh per ton the percentage of coal burned to coal raised would still be only 3%. It is not too optimistic, therefore, to suggest that the consumption of coal per ton raised could be reduced to at least half the present figure, representing a saving of nearly $\frac{1}{4}$ million tons of coal per annum for the steam and bituminous coal mines of South Wales. It is difficult to estimate the ratio of coal burned to the coal raised at present, because some coal is burned in the colliery boiler plant, some in the colliery generating stations and some in "selected" stations. Energy measured in kWh may be produced for any value between 1·2 lb and, say, 6 lb of coal burned per kWh. It will be argued, of course, that there is a vast difference between the calorific values, ash contents and prices of coal burned at the colliery and at the selected station, but other factors enter into the calculation, such as labour in handling the inferior coal and in disposing of the ash. With the increased value of coal the natural tendency is to up-grade inferior fuels by processing them, rather than to burn them in inefficient boiler plant.

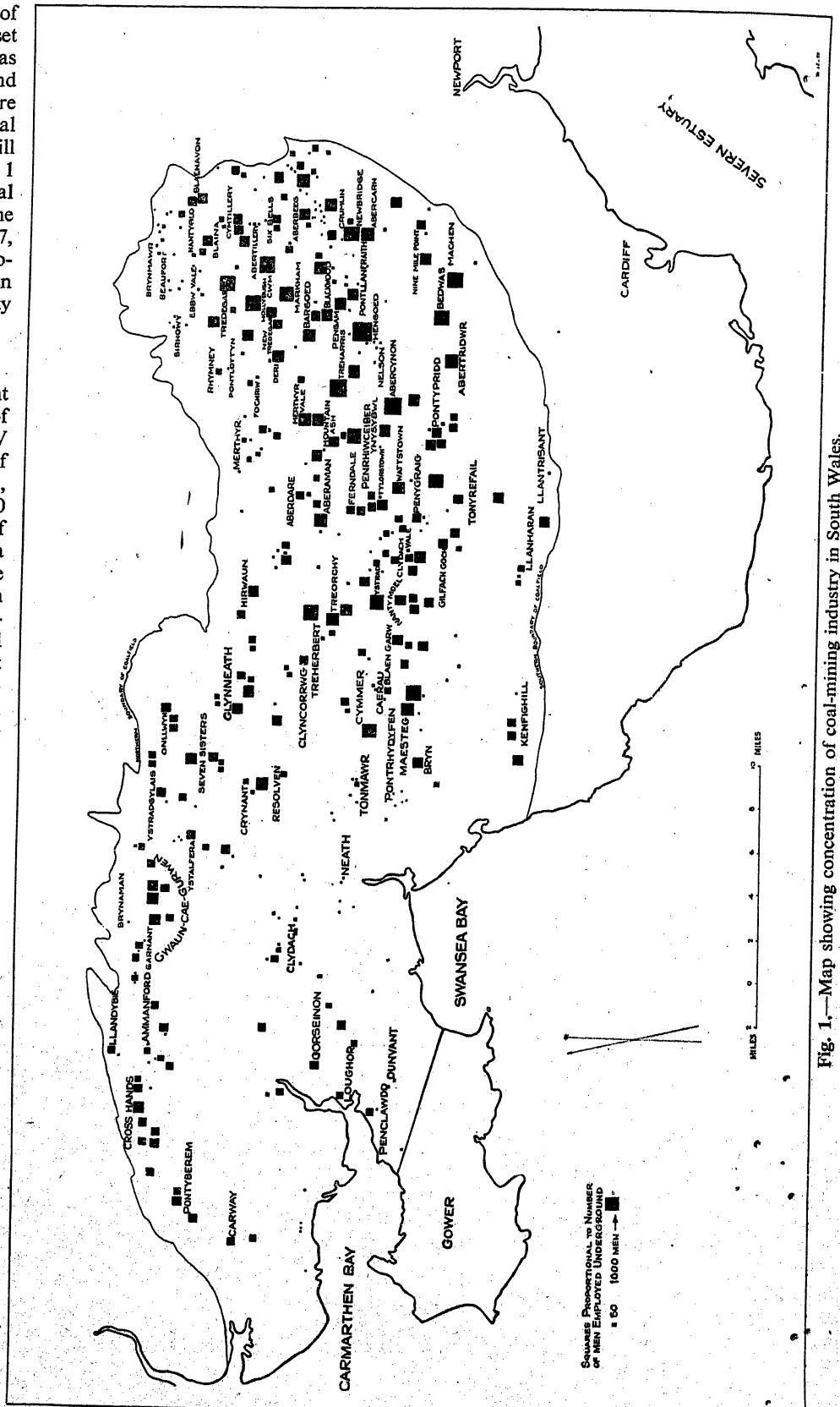


Fig. 1.—Map showing concentration of coal-mining industry in South Wales.

(3.2) A Method of Comparison of the Energy Consumption for Different Collieries

To improve the efficiency of the power consumption of the coal-mining industry generally it would be useful to have a standard by which the power consumption at different collieries throughout the country could be compared. For all-electric

collieries the unit of comparison is the number of kWh per ton of coal wound. For all-steam collieries, or for a self-contained group of mixed steam and electric collieries which generate all their own power, the percentage of coal burned to coal wound gives the necessary comparison. But there is still no basis of comparison between the all-electric colliery and the all-steam colliery except a cost basis, and no method of assessing the relative overall efficiency of a colliery importing power, either electricity or compressed air, from outside.

It is suggested that this be done on a B.Th.U. basis. For example:—

	Millions of B.Th.U.
Coal burned in colliery boilers, 1 600 tons at 12 000 B.Th.U./lb	43 000
Electricity imported, 380 000 units at 20 000 B.Th.U./kWh	7 600
Compressed air imported, 40 million ft³ at 50 B.Th.U./ft³	2 000
Total	52 600
Coal wound in same period	65 000 tons
Consumption, in millions of B.Th.U./ton wound ..	= 0·81

(In an all-electric colliery consuming 35 kWh/ton, assuming 20 000 B.Th.U./kWh, the consumption would be 0·7 million B.Th.U./ton.)

The figure of 20 000 B.Th.U./kWh represents an overall thermal efficiency of generation and transmission to the colliery busbars of 17%, and the compressed air is based on a figure of 400 cubic feet per kWh. These figures can be adjusted to meet actual local circumstances if required.

At a colliery with steam plant two factors affect the power costs, (*a*) the efficiency with which steam is raised, and (*b*) the efficiency with which the energy in the steam is utilized. Even though (*a*) may be high where the boiler plant is comparatively new and well maintained, (*b*) is usually low owing to the surface plant consisting of a number of scattered drives working on a low load factor and consequent high steam losses.

The electrification of surface plant is economically justified and the savings are correspondingly greater if obsolete steam plant is being replaced by new electric drives. Further discussion of the power costs is outside the scope of this paper.

(4) IMPORTANCE OF CONTINUITY OF SUPPLY

Power companies often emphasize to a consumer that reliability of supply is the first concern of the power company if for no other reason than a purely selfish one, as failure of supply means loss of revenue to the power company. To a colliery company, however, the loss is usually many times the loss to the power company.

Consider a shut-down at an all-electric colliery during the morning shift. The output is 1 500 tons/shift and there are 1 300 men employed. Electricity is charged at, say, 0·6d. per unit at to-day's price of coal. The colliery consumes 52 500 kWh/shift, or £131 worth of electricity. If the whole shift were lost the power company would lose £131 at the most, and the colliery company £1 744 revenue, assuming a pit-head price of 25s. per ton. But an hour's shut-down might mean the same loss to the colliery company, for if the fan stopped the men would have to be withdrawn. The next day's shift would also be dislocated. The loss to the power company would be less than £100. Even if the men are not withdrawn and the power is off for half an hour, 1 000 men may waste 500 hours at 2s. per hour, or £50, to say nothing of the general disorganization caused thereby.

The same loss is incurred by a colliery company with its own steam plant if the boiler auxiliaries, for example, are electrically driven and supplied from an outside source. Without steam, the winders, compressors and fan may all be stopped, although the loss in revenue to the power company will be negligible. Serious stoppages may endanger the whole pit if the length of stoppage exceeds the storage capacity of the pumping system and the pumps are allowed to flood. Adequate storage capacity provided underground is of great importance, as in addition to guarding against a failure of the electric supply to the pumps it also enables the load factor to be improved. It is advocated that all underground pumping stations should be so designed that all the water made in 24 hours can be pumped in 6 hours.

The need for a thoroughly reliable and adequate power supply under all weather conditions cannot be too strongly emphasized.

(5) SPECIAL PROBLEMS AFFECTING GENERATION IN COLLIERY DISTRICTS

As is well known, the coal mines in South Wales are distributed over a number of valleys divided by ranges of hills rising in some places to about 2 000 ft. At the top ends of these valleys the collieries themselves are frequently over the 700-ft contour. Geography therefore introduces special problems with regard to the erection of overhead transmission lines. The location of power stations must also be considered in relation to the hilly nature of the country. Although there is a river running down each valley the water supply is scarce at the top of the valleys and it is natural, therefore, that any large generating stations in the area will be erected to the south of the coalfield where several rivers converge. This means that if the collieries at the northern extremity of the area rely for their electricity on these central generating stations, they must be reached by an extensive network of transmission lines, which must inevitably cross the mountains at some points.

(5.1) Pit-Head Generation

This is considered here only in so far as it affects the transmission problems discussed, but it is clear from what has been said above that greater reliability of supply will be achieved if power is generated at several of the larger collieries or in the centre of groups of collieries. With the chemical treatment available to-day many pit waters which have been condemned in the past can be treated at a reasonable cost to make them suitable for the requirements of a generating station.

The advantages in favour of pit-head generation may be summarized as follows:—

(*a*) Greater security of supply.
(*b*) Reduced transmission losses.
(*c*) Reduced capital charges on transmission lines.
(*d*) Saving in coal freight and handling charges.
(*e*) Flexibility of disposal of slow-moving stocks of coal, or non-disposable washery by-products.
(*f*) Ease of disposal of ash along with washery refuse.

The disadvantages may be stated thus:—

(*a*) Greater operating costs for a number of small stations compared with large "selected" stations.
(*b*) Higher coal consumption compared with the selected station.

It is usual for colliery companies who operate their own generating stations to distribute the costs of their technical staff over both the collieries and the power station, and this tends to offset the extra supervision required by a number of smaller stations.

(5.2) Saving in Coal Freight and Handling Charges

By using fuel at the pit-head the saving in freight and handling

charges would be between 4s. and 5s. per ton. A saving of 4s. per ton at the standard coal clause ruling in the area would be equivalent to 0·0384d./kWh, or a reduction from, say, 0·6d./kWh to 0·5616d./kWh, representing a saving of 6·4%. The lower the cost of electricity the greater the percentage saving. This saving would offset the higher coal consumption compared with the selected station, as there is no reason why steam conditions of the order of 400 lb/in^2 (by gauge), 820° F, should not be adopted at the pit-head stations.

(5.3) Operating Colliery Generating Plant in Parallel with Grid or Power Company's Network

From the point of view of transmission and distribution the possibility of operating the colliery company's generating plant in parallel with the supply company's generating plant or in parallel with the Grid must not be overlooked. In fact, if a regional survey were made of the electricity supply requirements for an industrial area like South Wales, it would be found that there are many factors in favour of operating the colliery power stations as base-load stations and taking the peak demand from the Grid. Due to the absence of lighting load and reduction in domestic consumption at present, the peak demand on the Grid or public supply will correspond to the peak demand at the collieries, but in normal times the maximum demand on the Grid may again shift to the afternoon and evening, in which event there will be an advantage if the morning peak demand on the collieries were taken from the Grid. Fig. 2 shows the effect of this.

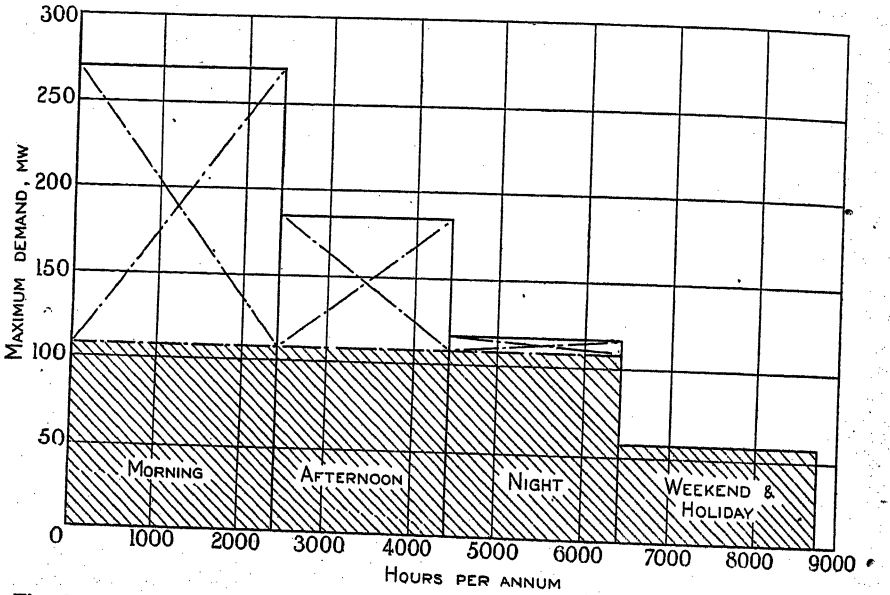


Fig. 2.—Diagram showing colliery maximum demand and proposed division in MW loading between colliery generating station and public supply.

(6) TRANSMISSION LINES IN SOUTH WALES

Owing to the heavy concentration of industry in South Wales and the foresight of the power company in meeting the demand by a widely distributed network, South Wales is well covered with transmission lines. Colliery companies and the power company have on the whole erected their lines regardless of each other, and as a result the utilization of available copper is not efficient and lines go over the high contours, which would not have been necessary if advantage could have been taken of existing circuits.

A study of the map of the transmission lines in South Wales illustrates the advantages which would result from regional planning to the benefit of both producers and consumers. A knowledge of the present loadings and an estimate of possible future loadings would be necessary before a comprehensive plan could be worked out in detail, but any scheme which enabled cheap electricity to be produced locally with minimum freight and transmission charges would have two important advantages; (*a*) it would help to attract new industries to South Wales, and (*b*) it would turn the South Wales coalfield into one of the largest electricity exporting areas in the country. The recent additions to the capacity of the east-west Grid lines would be of great assistance in this respect.

(7) ANALYSIS OF COLLIERY LOAD

(7.1) Power Consumption of Various Services

To assist in such a survey an analysis of a group of collieries producing 10 million tons per annum is given below. This shows that, assuming complete electrification, the power consumption of the various services would be as follows:—

	kWh/ton	Percentage
Ventilation	5·02	14·4
Pumping	5·27	15·1
Compressing	15·75	45·1
Winding	5·55	15·9
Miscellaneous	3·32	9·5
	34·91	100

Assume that collieries work 50 weeks per annum and that each week is divided up as follows:—5 days at 3 shifts per day; one Saturday morning shift; one week-end from Saturday 2 p.m. to Monday 6 a.m. (40 hours); holidays 15 days at 24 hours per day. This gives the following hours per annum:—

	hours
Morning shift	2 400
Afternoon shift	2 000
Night shift	2 000
Week-ends and holidays	2 360
	8 760

(7.2) Percentage Division of Units over Shifts

Table 1

	Morning	Afternoon	Night	Week-ends and holidays	Total
Ventilating	31	26	24	19	100%
Pumping	31·5	25	20·5	23	100%
Compressing	38	28	23	11	100%
Winding	64·5	23·2	10·7	1·6	100%
Miscellaneous	72·6	27·4	—	—	100%

From these figures the average kWh/hour during the various shifts can be found. The maximum half-hourly demand is calculated from the average demand by dividing by a factor of 0·92 to allow for seasonal and other variations, and on the assumption that the ratio of the maximum average to the maximum demand is in accordance with the following factors:—ventilating 0·985; pumping 0·985; compressing 0·91; winding 0·77; miscel-

Table 2

OUTPUT 30 × 10^6 TONS PER ANNUM.

Service	Consumption		Consumption per shift (× 10^6)				Maximum demand				Load factor
	Per ton	Total × 10^6	Morning	Afternoon	Night	Week-ends and holidays	Morning	Afternoon	Night	Week-ends and holidays	
	kWh	kWh	kWh	kWh	kWh	kWh	kW	kW	kW	kW	%
Ventilating	5·02	150·6	46·80	39·00	36·15	28·65	21 750	21 750	19 950	13 200	80
Pumping	5·27	158·1	49·80	39·60	32·40	36·30	21 800	21 750	17 850	16 800	80
Compressing ..	15·75	472·5	180·00	132·00	108·00	52·50	90 000	78 000	64 500	26 700	60
Winding	5·55	166·5	107·43	38·55	17·79	2·73	63 300	27 300	12 300	1 650	30
Miscellaneous ..	3·32	99·6	72·3	27·30	—	—	72 150	33 000	—	—	15·8
Total	34·91	1 047·3	456·33	276·45	194·34	120·18	270 000	181 800	114 600	58 350	45

laneous 0·45. Table 2 shows the distribution of consumption and maximum demand throughout the various shifts for an annual output of 30 million tons. These figures can be used *pro rata* down to, say, 10 million tons/annum.

(7.3) Probable Saving by Connecting to Public Supply

Fig. 2 shows the maximum demand throughout the year for 30 million tons. If the colliery generating plant supplied 40% of the maximum demand the load factor would be 83·5%. The energy supplied by the colliery generating plant would be 789·72 million kWh and by the public supply 257·58 million kWh. Assuming the public supply to be charged on the half-hourly maximum afternoon demand in the winter months, this would be 181 800 kW − 108 000 kW = 73 800 kW.

Ignoring the difference in fuel costs between the colliery generating stations and the public supply, and assuming a charge of £2·75 per kW maximum demand and 0·2d. per kWh with coal at 12s. 6d. per ton, the following charges are obtained:—

270 000 kW M.D. 1047·3 million kWh (L.F. 45%) = 0·37d./kWh.
Mixed generation 1047·3 million kWh = 0·315d./kWh.
Saving due to diversity of demand = £2·75 × (270 000 − 181 800) kW = £242 500.
Saving per million tons per annum = £8 085, or 2d. per ton of coal raised.

The above calculations assume the same cost of electricity whether received from the public supply or from the colliery generating station. It is clear, however, that further savings will result to the colliery company from generation at the pit head, particularly where a large demand is being supplied as in this instance, and the whole subject is worthy of more detailed study than can be given here.

The load/energy diagram in Fig. 3 shows the load factor for the different classes of load. The abscissae give the total kWh per annum and the ordinates the maximum demand in megawatts. For a maximum demand of 40 MW and a load factor of 100% the consumption per annum would be 40 × 8 760 × 1 000 = 350 million kWh. Thus the percentage load factors are marked off on the ordinate corresponding to 350 million units.

By generating 40% of its load a colliery company would safeguard the supplies to its vital services, namely ventilating and pumping, and would have a small margin in hand for winding and compressing should power from an outside source be cut off.

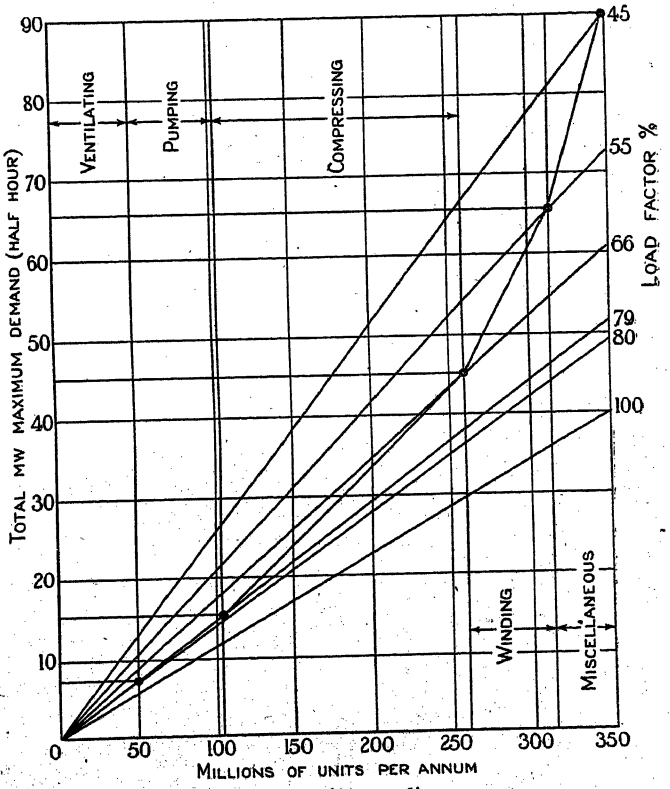


Fig. 3.—Load/energy diagram.

(8) DISTRIBUTION AT COLLIERIES

Based on a consumption of 35 kWh/ton and a load factor of 45%, the transformer capacity required to step down from the transmission network is 0·58T at 0·8 p.f., and 0·464T at unity power factor, where T is the tons of coal raised per week. For a 10 000-tons/week colliery two 6 000-kVA transformers would be required with one as standby. Alternatively three 3 000-kVA transformers might be adopted with one as standby. The choice depends upon the cost and the switching arrangement adopted. Usually the latter arrangement will be cheaper.

Assuming 500 MVA on the 33-kV busbars and 7·5% transformer reactance, the corresponding short-circuit MVA on the 3·3-kV busbars would be 69 MVA with two 3 000-kVA transformers in circuit. To this must be added the effect of any synchronous plant connected to the 3·3-kV busbars, say 10 MVA for a motor driving a 6 500 ft^3/min compressor. This gives a total of 79 MVA.

The above figures are for a colliery with no generating plant, but where there is generating plant as indicated in the typical diagram of connections (Fig. 4) the short-circuit value on the 11-kV busbars is 268 MVA, neglecting resistance, etc., or 61 MVA on the 3·3-kV busbars.

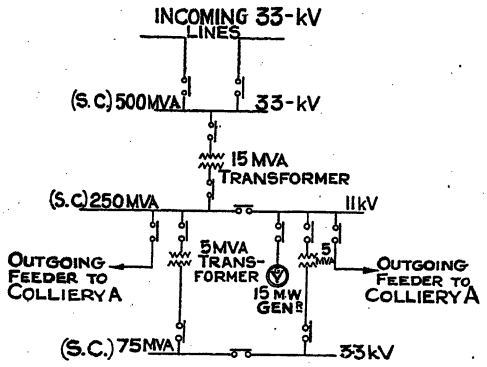


Fig. 4.—Switchgear diagram for colliery with 15-MW generator.

A colliery network represented by a hexagon with a 15 000-kW generating set at each corner and with sides 10 miles long and interconnected to include other collieries, is shown in Fig. 5.

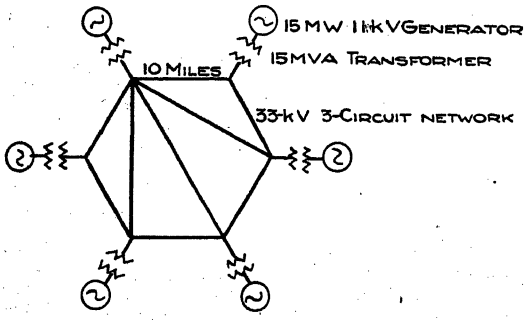


Fig. 5.—Diagrammatic arrangement of colliery generating system and network.

With single-circuit 33-kV transmission lines with a reactance of 0·56 ohm per mile the short-circuit capacity of the 33-kV busbars at A with all the machines running would not exceed 350 MVA.

Summarizing the above, it is clear that to meet nearly all requirements at collieries a few standard sizes of switchgear may be adopted; the following are recommended:—

33 kV:—500 MVA
11 kV:—250 MVA
150 MVA
3·3 kV:—75 MVA

By using 75-MVA 3·3-kV switches throughout the surface installation the use of reactors would be avoided and greater safety would be provided.

To protect old switchgear which has to meet an increased short-circuit current, h.r.c. fuses may be used to advantage as a substitute for reactors.

For pit feeders reactors will be required, as flame-proof 3·3-kV switchgear is usually designed for a maximum short-circuit rating of 25 MVA and it is an advantage to limit the short-circuit capacity underground to this figure.

Assuming two shaft feeders in parallel, Table 3 shows the percentage reactance which must be added for different lengths of shaft cable, to reduce the short-circuit value from 75 MVA to 25 MVA.

Table 3

Length of one cable	300 yards	1 000 yards
150 amp, 0·1 in²	4·4%	4·01%
200 amp, 0·15 in²	5·89%	5·39%
250 amp, 0·15 in²	7·37%	6·73%

Standardization of switchgear as outlined above is strongly recommended. It would rob manufacturers of their competitive novelties and purchasers of their individual fads and fancies, but the cost of electrical equipment for distribution and transmission prolongs the life of many an old stand of Lancashire boilers and of many a blast haulage and blast pump, although on the basis of running costs there is an overwhelming case for electrification.

The present-day price of a substation to feed a colliery from a 33-kV system, i.e. two incoming circuit-breakers, a bus-section switch and two transformer feeders, two 6 000-kVA transformers, three 3·3-kV circuit-breakers (two transformer feeders and one bus-section switch) and connections is approximately £3 16s. per kVA, based on 6 000 kVA maximum demand.

(9) CHOICE OF SWITCHGEAR

(9.1) Switchgear for Medium Voltage

Assuming two 300-kVA transformers with a reactance of 5% and 75 MVA on the 3·3-kV busbars, then with a medium voltage of 0·4 kV the short-circuit current will be approximately 15 000 amp, or 10 860 amp at 0·55 kV with the two transformers in parallel. This means that medium-voltage switchgear and control gear should be installed to meet these values, but very few medium-voltage switches in operation are adequate to deal with these conditions. If the motor control gear in series with switchgear is set to operate before the back-up switch, as is often the case, a dead short-circuit on the controller or motor may have disastrous results. Controllers should be used only for overload protection and not for short-circuit protection.[1]

The characteristics of a h.r.c. fuse are, however, such that a short-circuit would cause it to trip out in a very much shorter time than the control gear. Under ordinary overload conditions the controller would operate before the h.r.c. fuse. The cost of h.r.c. switch-and-fuse gear is very much less than that of an oil circuit-breaker for each outgoing circuit.

Difficulty is, however, involved in the use of h.r.c. fuse gear. The Amendments to the General Regulations Governing the Use of Electricity in Mines advocate that, in every circuit where the voltage exceeds 125 volts, earth-leakage protection shall be provided to open the circuit if the current to earth exceeds 15% of the rated current, or 5 amp, whichever is the greater. Earth-leakage protection has so far not been generally adapted to switch-and-fuse gear, and the use of this apparatus without earth-leakage protection is not, therefore, permitted. Representations have been made from several quarters for some relaxation of this Regulation before it becomes law, in so far as it affects medium-voltage circuits on the surface. The compulsory provision of earth-leakage protection on all outgoing feeders underground is welcome.

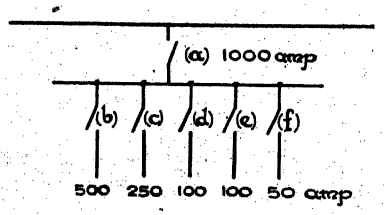


Fig. 6.—Application of proposed Regulation regarding earth-leakage protection.

A switch-and-fuse board for controlling the medium-voltage distribution on the surface would possibly have two incoming circuit-breakers, and earth-leakage protection might be fitted on

these. Earth leakage on incoming feeders is not an advantage as an earth fault on one outgoing circuit will shut down the whole board, and further, if there is a considerable difference in the currents in the outgoing circuits, it will not be possible to give the requirements of circuit interruption with 15-amp or 5% fault current, whichever is the greater.

The essential requirement of the proposed amended Regulations is that every part of the system shall be covered by earth-leakage protection. It is not intended that in the event of an earth fault that circuit only in which the fault occurs shall be isolated, provided that the sensitivity of the protection provided for the system as a whole is adequate for the branch circuit or circuits. In the discussion on these proposed amendments to the Regulations, Mr. Horsley cites a case to illustrate the inadequacy under certain conditions of leakage protection at the origin of the system only.[2]

A setting of 7·5% at (*a*) provides 15% protection for the circuit at (*b*), but for the other circuits (*c*), (*d*), (*e*) and (*f*) the protection thus provided at (*a*) would represent 30%, 75%, 75% and 150% respectively (see Fig. 6).

To provide 15% protection for the circuit at (*f*) by means of leakage protection at (*a*) only would require a setting of 0·75% at (*a*).

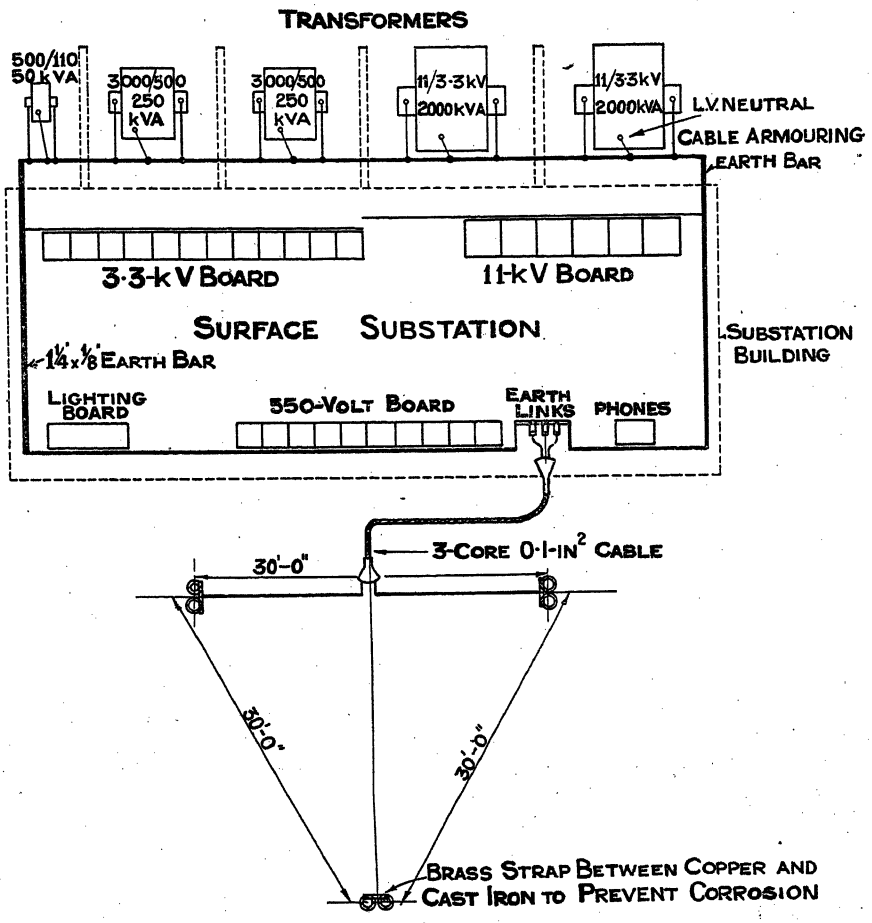


Fig. 7.—Earthing system on colliery surface.

(10) EARTHING

(10.1) Earthing Metallic Structures

Regulation 20 of the "Report of the Committee on the Amendment of the General Regulations Governing the Use of Electricity in Mines under the Coal Mines Act" deals with the question of earthing. Metallic structures that are required to be connected with earth shall be connected to one or more earth electrodes at the surface of the mine, by means of earthing conductors. The earth electrodes provided for this purpose "shall be constructed and maintained so that the resistance between the electrodes and the general mass of earth does not exceed 2 ohms." It is quite usual and permissible to use a number of electrodes such as pipes buried in the earth and connected together in such a way that the resistance of the whole arrangement does not exceed 2 ohms.

Fig. 7 shows a general arrangement for earthing at a mine. An earth bar is run round the substation and behind each switchboard, and to this earth bar are connected all those metallic structures requiring to be earthed. The same earth bar is also taken outside the substation for connection to the neutral point of the secondary of the transformers. Three links are shown in the connections to the electrodes. These are to facilitate testing, as by opening two links the resistance of two of the electrodes can be tested while still leaving the system earthed.

The armouring of the cables is also connected to this earth system, and it is through this armouring that metallic structures underground, which are liable to be charged by contact with live parts, are connected to earth at the surface of the mine.

A further point to note is that if the substation is fed by overhead lines from a generating station the earth system will be connected back through the earth conductor and the armouring of the cables to the earth plates along the route of the overhead line and to the earth at the power stations.

(10.2) Earthing Outgoing Feeders

Regulation 31(*d*) of the above Report reads:—

"For the proposals of paragraph (*c*) of this regulation, structural provision shall be made in the switchgear controlling the circuit, whereby the conductors may be connected with earth without danger to the operator."

The conductors cited under paragraph (*c*) include the proviso "if the voltage of the circuit exceeds 650 volts."

This means that on all circuits above 650 volts structural provision must be provided in the switchgear. This requirement has up to now not been treated with the consideration that it deserves. It is usual to make provision in draw-out switchgear for some extension plugs to be provided whereby the outgoing feeder may be connected to earth, but these extension plugs and the associated earthing arrangement are difficult to fit and their design has not altered since M.D. Circular No. 23 was issued in 1927. To ensure that earthing is carried out properly when a repair is being undertaken and time is short, it is essential that an efficient and easily applied earthing device be provided. Furthermore, it is not clear whether extension plugs come under the category "Structural provision in the switchgear."

With non-drawout switchgear it is simple to provide an isolating switch with "on," "off" and "earth" positions, although

it is strongly recommended that the isolation should be visible to ensure that all three blades engage.

With draw-out switchgear of the truck type, where clearances permit, it is recommended that an earthing switch be included inside the truck portion. The procedure would be to withdraw the truck, close the earthing switch inside the truck, re-engage the truck and close the breaker, at the same time rendering it non-automatic.

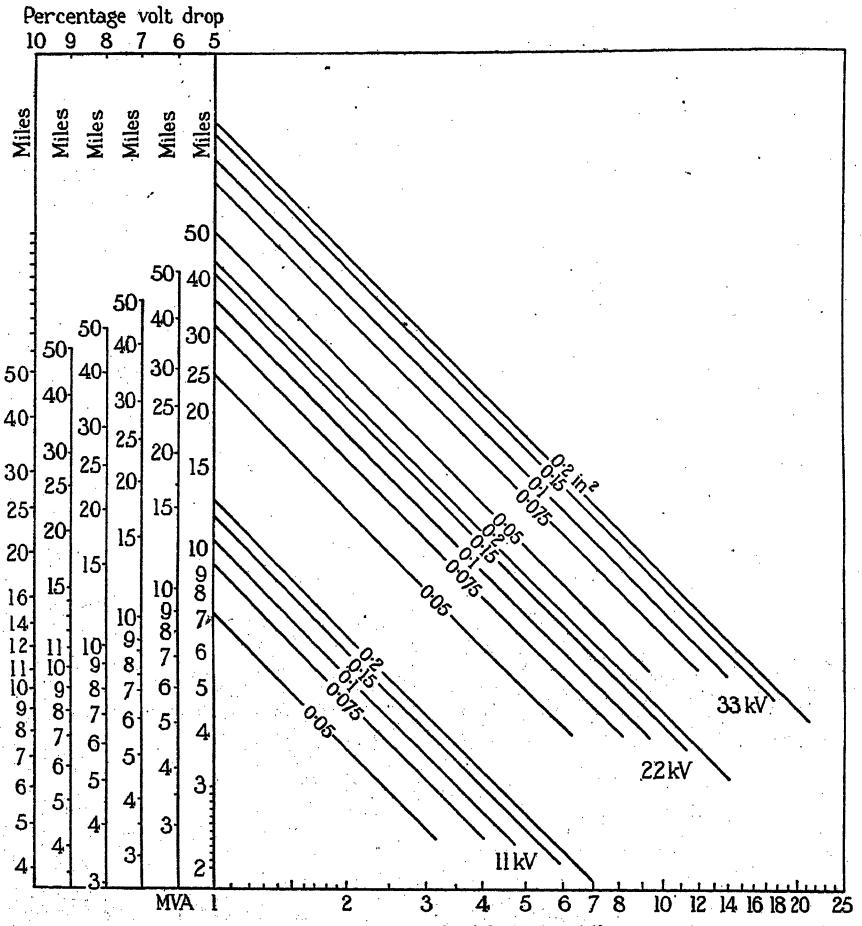


Fig. 8.—Carrying capacity of overhead lines.

On compound-filled metal-clad gear of the flame-proof type up to 25 MVA it is possible to obtain switchgear with an internal earthing switch, but above this size there is insufficient room to accommodate an earthing switch of suitable size in the tank. A better arrangement than the extension plugs already referred to would be to have a separate earthing switch on its own carriage, which could be racked-in in place of the feeder breaker requiring to be earthed. The best solution to ensure that the Regulation is carried out with safety is to provide an earthing switch with each breaker, and the attention of switchgear designers is called to this important requirement.

(11) THREE-CIRCUIT OVERHEAD LINES

In their paper "Standardization in Great Britain of Single-Circuit Overhead Lines up to 33 kV"[3] Messrs. Taylor and May make a strong plea for standardization of overhead line construction. With this the author is in agreement. A few existing designs are illustrated in that paper, and the striking thing about all these designs is the flimsiness of the construction of the cross-arms. The 33-kV construction advocated is a wooden H-pole with suspension insulators and the conductors in the same horizontal spacing. This is a standard design, and many miles of overhead line with this construction are in service in South Wales. One of the objections to an H-pole construction, particularly in hilly country, is the cost of erection and the necessity for an extremely accurate profile of the route. On the other hand, any flat spacing of conductors permits the spacing to be readily increased where exceptionally long spans are called for by the profile of the route. The flexibility due to suspension insulators is also claimed as an advantage.

An alternative suggestion is here put forward for a single-circuit wood-pole line using post-type insulators and a delta spacing. The same design could also be used for 11-kV and 22-kV lines, and there seems little advantage to be gained by altering the spacing. Details of the cross-arm are given later.

(11.1) Carrying Capacity

The standard method of calculation for voltage drop as applied to short lines is adequate for the distances under consideration and has been used throughout.

In Fig. 8 curves have been drawn to show the MVA-miles which can be transmitted by different sizes of conductors at different voltages for voltage drops from 5% to 10%.

The right-hand extremity of these curves gives the maximum MVA which can be carried for a 72 deg F temperature rise.

The curves have been calculated on the basis of a 60-in spacing.

(11.2) Influence of Spacing of Conductors

The influence of spacing on the impedance per mile and, therefore, on the voltage drop, is shown in Table 4. The impedance at 60-in spacing is taken as unity.

Referring to the curves drawn in Fig. 8 for MVA-miles for three 11-kV, 0·15 in² conductors, for example, 5% voltage drop is 0·55 kV with an equivalent impedance of unity. For a spacing of 36 in the equivalent impedance would be 0·941 and the voltage drop, therefore, 518 volts or 4·7%. Corresponding to a 10% drop for 60-in spacing the drop for 36-in spacing would be 9·4%, for 0·15 in² or 9·2% for 0·2 in². The error in selecting the MVA-miles from these curves will not be sufficient, therefore, to influence the size of conductor.

Table 4

Spacing, in	30	36	42	48	54	60	66	72
0·05 in²	0·964	0·973	0·98	0·987	0·995	1	1·003	1·011
0·075 in²	0·941	0·955	0·969	0·981	0·99	1	1·007	1·017
0·1 in²	0·926	0·945	0·961	0·975	0·989	1	1·01	1·021
0·15 in²	0·906	0·941	0·951	0·97	0·986	1	1·012	1·027
0·2 in²	0·894	0·921	0·945	0·966	0·984	1	1·016	1·029

These figures also illustrate that there would be very little objection to standardizing on one cross-arm for 11 kV, 22 kV and 33 kV. 22 kV is included in these considerations as a number of collieries still use this voltage, although from the point of view of standardization 22-kV transmission should be eliminated.

(11.3) Length of Span

Length of span or, more accurately, dip determines to a large extent the conductor spacing, and here again there is no standard practice in this country. The Cable Research Handbook (vol. II) recommends 26 in for voltages up to 11 kV, and 38 in for 33 kV, without any reference to span or dip. A reference is also made in the C.M.A. Handbook to a German formula which relates the spacing to dip and voltage but gives higher figures than are current practice here.

It is not necessary to have a different value of conductor spacing for every variation in dip and voltage, but it would be preferable to select a few standard pole-top fittings and to specify the maximum dips for which they could be used. Up to 33 kV the voltage would not greatly influence the choice.

(11.4) Influence of Span Length on Cost

A careful comparison has recently been made for an actual transmission line with three 0·15 in^2 conductors, a route length of approximately 3 miles and a voltage of 33 kV between a light cross-arm construction with span lengths not exceeding 380 ft, and a more robust cross-arm construction and span lengths up to 600 ft. In the first instance, ordinary pin-type insulators with 1 000-lb spindles were included, and in the second instance post-type insulators with 2 800-lb spindles. Details of the costs of the two lines at present-day prices are given in the Appendix. For the comparison the line was laid out in each case on the profile to select the best position for the poles and to take full advantage of the contour of the route. The stronger cross-arm construction is illustrated in Fig. 9.

(11.5) Design of Cross-Arms and Failures due to Icing

The design of cross-arms and the possibility of their standardization is a subject which demands attention.

During the ice storm of 1940 hundreds of cross-arms were twisted beyond repair owing to broken conductors. Very few cross-arms are designed to withstand the stress if one conductor breaks. Although the breaking of a conductor is an unlikely occurrence except during very severe weather conditions, the majority of cross-arms seem altogether too flimsy, and will usually twist in the direction of the line before a pin-type insulator will bend its spindle. Just how far twisted cross-arms relieved the stress on the masts themselves is difficult to say, as where conductors broke due to ice loading the mast usually collapsed at one point or another. Some towers collapsed without much damage because of inadequate foundations, but the majority of steel lattice masts gave way at a point about two-thirds of their height above ground.

All types of masts suffered and, owing to the variety of constructions in use, it was not possible to say whether one particular design would have fared better or worse had the direction of wind on that particular line been different. In some instances the cross winds certainly have caused conductor failures which would not have happened due to the ice loading alone.

One Kay pole line came down with particularly disastrous results, and it was found on examination that the locating projection on the upper vertical member which fits tightly into one of the four legs had broken off in each case. The justification for the Kay pole design, which needs considerable maintenance both for painting and inspection of the stays, was never really apparent except in very remote and mountainous countries where the Kay pole would be easy to transport.

The suggestion put forward by the late Mr. Borlase Matthews to standardize on a pressed-steel or plastic cross-arm for 3-wire lines fitted with pin-type insulators is interesting and will no doubt be followed up after the war for use with light lines up to, say, 11 kV.

Fig. 9 shows the design of the cross-arm already referred to which has been adopted for a 33-kV, 3-circuit, 0·15-in^2 overhead line. It consists of a 5in diameter pipe with flattened ends to take the insulators, and welded on to the back of a channel.

This cross-arm has been tested when fixed in position on an 8½in diameter pole-top with a pull of 2 800 lb applied at a

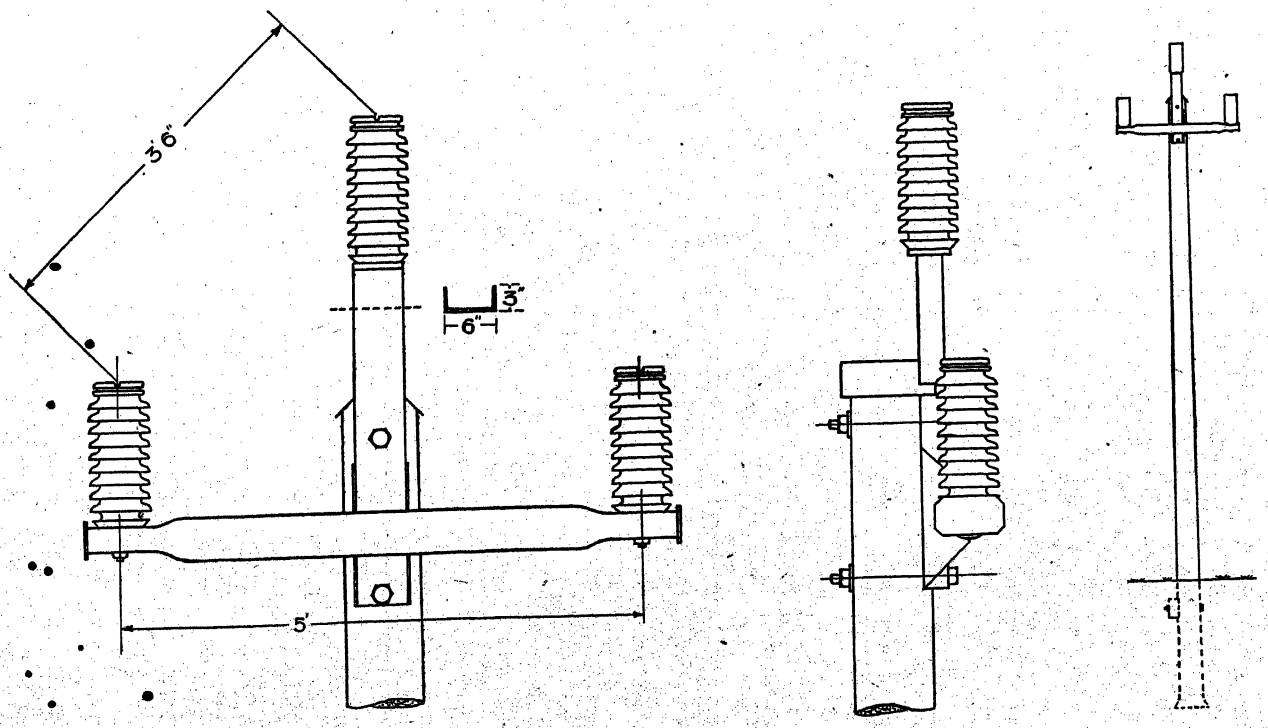


Fig. 9.—Outline of new design of cross-arm for single-circuit wood-pole lines.

leverage of 17 in corresponding to the height to the conductor groove of a 33-kV line post insulator.

The load was applied in three directions as follows:—

(*a*) Longitudinally in the direction of the line to represent the out-of-balance pull, due to, say, a broken conductor.
(*b*) At right angles to the line to represent wind loading.
(*c*) Vertically downwards to represent a dead-weight load due to ice.

No sign of permanent deformation could be detected in any of these tests, and no damage was sustained by the pole surface or by the bolts which attach the fitting to the pole. There was no movement of the fitting relative to the pole.

The usual design of cross-arms made from 4in × 2in channel or 3in × 3in angles and used with pin-type insulators with 1 000-lb spindles will not withstand, without permanent twist, a pull of more than 450 lb in the direction of the line at a leverage of 14½ in, which is the height to the conductor with a standard 33-kV pin-type insulator.

In addition to the great strength of the fitting illustrated, it has the advantage of being fixed to the pole by only two bolts and is self-aligning owing to the upright channel member gripping the pole surface. This grip also prevents any large out-of-balance pull from tilting or twisting the fitting from its original position, while at the same time preventing any tendency to split the pole. No notching or machining of the pole is required beyond drilling the two fixing holes.

The post-type insulators used have a strength of 2 800 lb, so that, when used with the fitting described above, a stronger construction is obtained and longer spans are possible, thus effecting the economies indicated in the Appendix.

(12) OVERHEAD LINE REGULATIONS

After the very severe ice storms of 1940 and 1941 attention was focused on the Overhead Line Regulations, which, as is well known, stipulate that the working load in conductors shall not exceed half the breaking load when they have a covering of ice equal to a radial thickness of ⅜ in at a temperature of 22° F and are subjected to a wind pressure of 8 lb/ft² calculated on the whole of the projected area of the ice-covered line.

For low-voltage lines the same Regulations apply except that a covering of $\frac{3}{16}$ in radial ice is stipulated instead of ⅜ in.

Many suggestions have been put forward for a revision of the Regulations,[4] and it is to be noted that in countries where ice loading is to be expected, e.g. America and Sweden, the regulations grade the ice loading to suit the localities. This seems a more rational basis than grading on a basis of voltage according to the Electricity Commissioners' Regulations.

Experience gained in the ice storms mentioned above proved, as was to be expected, that vulnerability varied directly with altitude, but at the same time the direction of the wind had a noticeable effect. Obviously if the line was running in the direction of the wind at the time of the trouble, it was much less likely to fail than a line at the same altitude at right angles to the wind. New lines erected in South Wales since the ice trouble have endeavoured to avoid high contours even at the cost of a considerable increase in the length of the line. Owing to the nature of the country, however, it is impossible to avoid crossing some of the ranges of hills which divide the valleys, and the altitudes at the top ends of the valleys are sufficiently high to cause ice formation. Some ice formation occurs nearly every year.

Table 5 shows a comparison between the sags in three sizes of conductors, 0·1, 0·15 and 0·2 in², for ice loadings of ⅜ in and ¾ in. All calculations are based on a factor of safety of 2. Figures are also given for the weight of ice to break these sizes of conductors when erected to meet the specified conditions. The effect of imposing a ¾-in ice loading, for example, for altitudes

Table 5

0·1 in² conductor, 7/·136 in, o.d. 0·408 in								
Span, ft	180	210	240	300	360	400	450	
22° F, no wind, and ⅜ in ice, sag (ft)	1·5	2·04	2·67	4·17	6·0	7·4	9·375	
60° F, no wind, no ice, sag (ft)	0·78	1·106	1·51	2·58	4·07	5·3	7·1	
Weight of ice to break, lb/ft	5·78	4·86	4·26	3·4	2·88	2·64	2·4	
22° F with wind and ¾ in ice, sag (ft)	2·69	3·66	4·79	7·48	10·79	13·3	16·85	
60° F, no wind, no ice, sag (ft)	1·13	1·83	2·77	5·32	8·59	11·15	14·62	
Weight of ice to break, lb/ft	6·5	5·72	5·16	4·48	3·99	3·8	3·62	

0·15 in² conductor, 7/·166 in, o.d. 0·498 in									
Span, ft	180	210	240	300	360	400	450	500	600
22° F with wind and ⅜ in ice, sag (ft)	1·24	1·69	2·2	3·44	4·95	6·12	7·74	9·56	13·75
60° F, no wind, no ice, sag (ft)	0·77	1·08	1·44	2·37	3·60	4·59	6·03	7·7	11·7
Weight of ice to break, lb/ft	7·6	6·88	6·06	4·9	4·09	3·7	3·36	3·04	2·62
22° F with wind and ¾ in ice, sag (ft)	2·09	2·84	3·72	5·81	8·36	10·32	13·08	16·15	23·2
60° F, no wind, no ice, sag (ft)	0·944	1·41	2·02	3·79	6·16	8·09	10·78	13·85	
Weight of ice to break, lb/ft	8·78	7·88	7·04	5·86	5·16	4·8	4·55	4·34	4·02

0·2 in² conductor, 7/·193 in, o.d. 0·579 in									
Span, ft	180	210	240	300	360	400	450	500	600
22° F with wind and ⅜ in ice, sag (ft)	1·1	1·5	1·96	3·06	4·4	5·43	6·875	8·49	12·22
60° F, no wind, no ice, sag (ft)	0·78	1·07	1·42	2·29	3·42	4·32	5·62	7·1	10·63
Weight of ice to break, lb/ft	11·0	9·4	8·3	6·4	5·4	4·88	4·36	3·98	3·4
22° F with wind and ¾ in ice, sag (ft)	1·77	2·42	3·16	4·93	7·1	8·77	11·1	13·7	19·7
60° F, no wind, no ice, sag (ft)	0·89	1·28	1·79	3·18	5·11	6·67	8·91	11·5	17·5
Weight of ice to break, lb/ft	11·4	10	8·86	7·34	6·4	5·94	5·46	5·18	4·8

over 800 ft would be to reduce the span lengths for the same sag.

From the Table it will be noted that, according to the Regulations, a 0·15-in² conductor would be sagged up to 11·7 ft at 60° F with no wind and no ice, but under these conditions it would require only 2·62 lb/ft of ice to break the conductor. If the Regulations were altered to demand an ice loading of $\frac{3}{4}$ in radial ice at 22° F with 8 lb/ft² wind pressure above a contour of, say, 800 ft, the maximum span length for the same sag at 60° F would be approximately 420 ft, and the weight of the ice to break the conductor would be about 4·75 lb/ft.

For level country, if the normal erection sags were limited to 10 ft at 60° F, the limiting spans would be approximately:—

Conductor, in²	0·1	0·15	0·2
Span length ($\frac{3}{8}$ in radial ice), ft	520	550	600
Span length ($\frac{3}{4}$ in radial ice), ft	390	425	475

Some such revision is recommended as it would give a greater margin of safety at high altitudes. Cross-arms and poles should be designed to give equivalent strength. If the Regulations were altered in this way to give different tensions in the conductors at different altitudes, it would be necessary to have straining points before altering the tension in the conductor.

(13) CONCLUSION AND ACKNOWLEDGMENT

The magnitude of the potential colliery electrical load should be given full consideration in any plan for the generation, transmission and distribution of electricity in any industrial mining area.

Electrification of the collieries in any area would be simplified and cheapened by more standardization of the sizes of units adopted. Standardization could be applied with advantage to switchgear, transformers, compressors, haulages, winder drums, transmission-line cross-arms, cable sizes, voltages, etc.

The subject of pit-head generation has been touched on in this paper only in so far as it affects the general problems of transmission and distribution, but it is one which demands full and thorough technical investigation in all its aspects, and in relation to the location of washeries, existing generating stations and transmission lines, coal freights and other local industrial loads.

Having weathered two major wars and a long intervening period of depression, the mining industry, which is still one of our major material assets, should now be modernized and re-equipped to a uniformly high standard in order to be able to cope with post-war problems.

The author wishes to thank Powell Duffryn, Ltd., for permission to publish this paper.

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(3) H. W. TAYLOR and K. L. MAY: "Standardization in Great Britain of Single-circuit Overhead Lines up to 33 kV," *Journal I.E.E.*, 1943, **90**, Part II, p. 233.

(4) J. MCCOMBE: "Amend the Overhead Line Regulations," *Distribution of Electricity*, 1942, **15**, p. 28.

(15) APPENDIX: COMPARATIVE COSTS OF SINGLE-CIRCUIT OVERHEAD LINES

(15.1) Construction Incorporating Cross-Arm shown in Fig. 9

Terminal Pole.	
Fittings	£74 3s. 6d.
Erection	£20 0s. 0d.
	£94 3s. 6d.
H-angle Pole with Post-type Fly-over Insulators.	
Fittings	£27 19s. 3d.
Erection	£17 10s. 0d.
	£45 9s. 3d.
Intermediate Straight-Line Pole.	
Fittings	£12 4s. 6d.
Erection	£10 0s. 0d.
	£22 4s. 6d.
Cost of Line.	
2 terminal-pole fittings as above	£188 7s. 0d.
31 intermediate straight-line pole-top fittings as above	£691 19s. 6d.
5 angle-pole fittings as above	£227 6s. 3d.
Wood poles	£399 16s. 9d.
	£1 507 9s. 6d.
49 700 ft 0·15 in² copper	£1 170 0s. 0d.
	£2 677 9s. 6d.
Supervision and engineering, 20%	£535 9s. 8d.
TOTAL	£3 212 19s. 2d.
Cost per mile for 3·05 miles—£1 052	

(15.2) Lighter Construction with 1000-lb Insulator Spindles

Fittings for, and Erection of, Terminal Pole.	
As above	£94 3s. 6d.
Fittings for H-angle Pole with Ordinary Pin-type Fly-over Insulators.	
Otherwise as above	£43 2s. 3d.
Intermediate Straight-Line Pole.	
Fittings	£6 11s. 3d.
Erection	£10 0s. 0d.
	£16 11s. 3d.
Cost of Line.	
2 terminal-pole fittings as above	£188 7s. 0d.
56 intermediate straight-line pole fittings as above	£927 10s. 0d.
6 angle-pole fittings as above	£258 13s. 6d.
2 long-span H-poles	£67 10s. 6d.
Wood poles	£387 6s. 3d.
	£1 829 7s. 3d.
Copper as above	£1 170 0s. 0d.
	£2 999 7s. 3d.
Supervision and engineering, 20%	£600 0s. 0d.
TOTAL	£3 599 7s. 3d.
Cost per mile for 3·05 miles—£1 180	

DISCUSSION BEFORE THE TRANSMISSION SECTION, 9TH FEBRUARY, 1944

Mr. J. A. B. Horsley: Excluding pit-head generation (literally), it is not clear how transmission lines over exposed hill-tops can be avoided in a centralized supply for groups of collieries, in view of the duplication of sources of supply and transmission lines essential for continuity of service.

The author states that the South Wales coalfield differs from other mining areas in two important respects—namely, the heavy pumping load and the extensive use of compressed air. As to pumping, the horse-power of electric motors allocated to that purpose in 1938 amounted to 19·4% of the total horse-power of

motors installed at all collieries in Great Britain; while the comparable figure for South Wales was 18·8%, and for Scotland 33·2%. With regard to compressed air, this it appears is responsible for a relatively extravagant use of power which the author suggests could be reduced to one-fourth or one-fifth if direct electric drive were substituted. In an analysis of the probable consumption of energy in a group of completely electrified collieries, the author allocates 15·75 kWh/ton for compressing air and 15·84 kWh/ton for pumping, ventilation and winding added together.

Mechanization of the coal face in 1938, as measured by the proportion of the total output obtained by machine mining, is shown by the following figures: coal cutting, 57·9% for Great Britain, 25·8% for South Wales; coal conveying, 53% for Great Britain, 43·9% for South Wales. Of the machine-cut coal, 70·6% was credited to electricity for Great Britain and 18·4% for South Wales. Of the coal conveyed, 63% was credited to electricity for Great Britain and 8% for South Wales. These figures speak for themselves.

The author desires to rationalize the ratings of circuit-breakers and transformers. He may succeed for his own group; if he can carry the whole industry with him he will have secured a notable triumph.

The author refers to earth-leakage protection. This is primarily an insurance against fire risk in the mine. He points out certain objections, of an economic rather than of a technical nature, to applying selective leakage protection to the surface installation. I am not sure, however, that he will secure selective isolation of a faulty circuit by the substitution of h.r.c. fuses, or by reliance upon normal overload protection; but it may be that the fire risk above ground can be discounted.

Mr. H. V. Pugh: The author's suggestion of having a number of small stations quite close to the concentration of collieries is a good one, and could be worked quite well in South Wales. There appears to be no objection to having single-unit, single-boiler power stations situated on the six main rivers in the district, so that they could work without cooling towers, and their position could be such that they could reach most of the collieries by overhead lines up the valleys. That would be better done, however, by the power company in the area.

The author's estimate of the saving possible by colliery electrification is on the conservative side, for collieries are rather liberal in their use of coal.

Mr. G. Cluley: In Section 5.3 the question of parallel running with the Grid is mentioned. I suggest that very careful consideration is necessary before connecting a colliery grid to the National Grid, as there are many disadvantages in this. With a self-contained system as indicated in Fig. 5, there is no need to rely on the National Grid for continuity of supply; the six stations shown should be quite sufficient reserve capacity without coupling to the Grid and also without affecting the economics of the scheme. No mention is made how this colliery grid would be operated.

Section 6 refers to the possibility of exporting large bulks of power from the South Wales coalfield. For this, large power stations would be required which would probably negative any suggestion of a separate colliery grid.

In Section 8 the author says that, assuming 500 MVA on the 33-kV bars and 7·5% transformer reactance, the corresponding short-circuit MVA on the 3·3-kV bars would be 69 MVA with two 3 000-kVA transformers in circuit. I agree with this figure if the 7·5% reactance refers to the 15-MVA transformers on the 33-kV bars, and the 3 000-kVA transformers have approximately 5% reactance. The author further says that these figures are for a colliery without generating plant, but where there is generating plant, as shown in Fig. 4, the short-circuit on the 3·3-kV busbars would be 61 MVA, actually less than without generating plant. I calculate that the short-circuit on the 3·3-kV busbars with a 15-MVA generator having, say, 10% reactance would be 87 MVA, not taking into account other synchronous plant. I suggest that a figure of 75 or 87 MVA is high for 3·3-kV switchgear, and too high for the average colliery scheme.

I agree that the maximum breaking capacity of mining switchgear proper should be kept down to a figure of 25 MVA, and if we attempt to bring the short-circuit current down from 75 MVA to 25 MVA by means of cable impedance or external reactance the voltage drop will be excessive.

The author's views on the standardization of switchgear are appreciated. Greater standardization has been effected in the flame-proof gear than with any other industrial gear, due primarily to the necessity for a flame-proof certificate and the willingness of the users to accept the minimum of attachments, such as watt-hour meters and special relays. Whilst on the subject of standardization, it is opportune to mention the proposed new Regulations regarding the design of switchgear for use underground. Section III, p. 5, states that "there shall be a positive requirement that all such apparatus shall be maintained in a safe condition and that the opening of any flame-proof enclosure, where this would expose live parts to the atmosphere, shall be specifically forbidden, in places where flame-proof enclosure is required." This proposal has had a very great effect on switchgear, and means, in effect, that almost all the existing gear of the draw-out type must be redesigned in spite of the fact that it has given very satisfactory service.

In Section 9 the author refers to the use of h.r.c. fuses and points out the difficulty with regard to earth leakage with fuse-gear. My own experience points to the necessity for earth-fault protection, particularly on all low- and medium-voltage systems.

I am glad to see that the author deals with the subject of earthing (Fig. 7). It is not generally realized that adequate earthing of apparatus is more important on low-voltage systems than on high-voltage systems, as there is so little voltage available to produce fault currents sufficiently large to operate the protective devices.

Mr. J. R. Cowie: Section 3 shows that it is advantageous to electrify the colliery as a whole; yet the problem varies with each colliery. I feel that the author's figures for the totally electrified colliery show that in it alone the maximum efficiency may be expected.

In Section 4 the author refers to the importance of continuity of supply. The consideration of all that may happen to a colliery, if there is a total cessation of the supply of electricity, is a much more powerful argument for continuity of supply than any cash criterion.

I am disturbed by the suggestion that a colliery or a group of collieries should generate its own electricity; that policy has been the bugbear of electricity generation in this country. People have been permitted to generate electricity who should never have been allowed to do so and this has delayed the realization of the advantages which the planners foresaw from the creation of the Grid.

I have on previous occasions suggested that the time would come when 20 000 or 30 000 volts would be used for distribution in the streets of our big cities. Other countries are thinking of 110 000 or 132 000 volts, not on main trunk lines but on distributors, and in some towns in this country it is thought that 132 000 volts will be necessary for main distribution to keep the supply going. In three countries about 300 000 volts is being applied to the main busbars, with voltages of 110 000 to 132 000 on distributors. Since it is suggested that a group of collieries should be permitted to generate electricity and take it over the hills of Wales, it is obvious that the main power-supply scheme must bear these possibilities in mind.

Regarding switchgear, we should take a larger view of the

matter. In various parts of the world, flame-proof switchgear complying with our latest regulations is being put underground; its rating is 6 600 volts, giving an output of 50 MVA. Moreover, attempts are being made to build switchgear to deal with 75 MVA for use underground. In the coalfields where this switchgear is being put in, the coal seams are 30–50 ft thick, as against many 9in seams of Scotland and 3–4ft seams in Wales. Everything depends on the individual pit, and no one answer applies to them all.

I am perturbed by the suggestion that a 410-volt switch has normally to carry 3 000 or 4 000 amp, 410 volts. With short-circuit amperes of about 43 000 for 25 000-MVA rupturing capacity this is not encouraging from the point of view of the switchgear designer and indicates changing to a higher supply voltage.

Mr. R. C. Andersen: The author has done a great service to the industry by pointing out that when the consumer is an important all-electric colliery company the loss of a morning's shift through a failure of electric supply can cost the company no less than £1 744. The supply company's loss in the circumstances specified is no more than £131.

For a long time I have been pleading that transmission-line design per line should be inspired by the potential overall cost per outage. Clearly, potential outage cost should determine design; I call this determination the rationalization of line construction. On the other hand, to standardize for standardization's sake may seem very impressive technically, but economically it can be disastrous. With this thought in mind, it is not surprising that the author after paying such respect to standardization as convention demands, flatly rejects—for colliery supply in his South Wales area—the designs advocated by Messrs. Willott Taylor and May in their paper "Standardization in Great Britain of Single-Circuit Overhead Lines up to 33 kV."* He uses in their stead the construction shown in Fig. 9 and described in Sub-sections 11.1 to 11.5 of his paper. Here each component is much more costly than the cost of the components advocated by Willott Taylor and May, but the Appendix establishes that none the less a saving per mile of £128 is obtained with the author's construction. Additional gains are puncture-proof insulators, high-efficiency insulation under deposit conditions, an insulator strength of 2 800 lb, a pole-top construction strength of 2 800 lb, a marked decrease in insulator hazard by the simple process of using longer spans, and increased ability of the construction to withstand ice storms, gales and the like. A disadvantage is the unique circumstance that the insulators are not amenable to periodical live-line testing. Against this can be set the very comforting fact, that over a period exceeding ten years, replacements of these insulators per annum have been at the remarkably low level of 0·016%.

Though the author's transmission-line recommendations are specific to colliery electrification in South Wales, the principles underlying these recommendations are, in my view, of such vital importance that they deserve the fundamental recognition that is their due. They underline what I submit should be accepted as an axiom. First, determine the potential cost per outage to supplier and consumer combined on a given transmission line; then design that line to the outage cost.

Mr. A. R. Cooper: In his overall classification of the South Wales group, the author points out that, if all the collieries in the area under consideration were completely electrified, the overall demand would be about 270 MW with a load factor of about 45%. This is equivalent to the output of a good-sized modern station. The chief objections to locating all the generation on one site, particularly for this type of load, are (*a*) unreliability of the transmission system, and (*b*) the need for using the lowest grades of fuel at the pit-head wherever possible.

Where security is of such vital importance and where most interruptions of supply are due to weather conditions, there would seem to be a strong case for interconnecting collieries by underground cable instead of by overhead line. It may be noted that the London cable system, which is chiefly at 66 kV, connects a load rather bigger than that specified by the author. It covers an area of some 250 square miles and has a security of almost 100%.

When discussing the use of low-grade fuels, the author in Section 3.1 refers to a consumption of 1·5 lb of coal to deliver 1 kWh at the 3·3-kV busbars. One can only conclude that this must be particularly good coal, and this impression is supported by the statement in Section 3.2, where he refers to coal having a calorific value of 12 000 B.Th.U. This fuel is far better than the coal normally carried hundreds of miles to selected stations. In Section 7.3, reference is made to a coal price of 12s. 6d. a ton. I should be glad if the author would indicate whether this price applies to the coals referred to above, and if so what quantities are available. I thought that the strong case for pit-head generation was that it made possible the burning of such low-grade fuels as slurry, fines and anthracite duff which were not worth transporting. There is no difficulty in designing plant specially to burn these fuels; in Australia, fuel having a calorific value of some 3 000 B.Th.U./lb is being satisfactorily burnt.

In Section 5.3, the author recommends parallel operation with the Grid system, and suggests that the local colliery plant be given base load, and that the peak loads be taken from the Grid. This question is too big to be treated as a side-issue, but as a generalization one can say that the most uneconomic way of buying power from the Grid is to buy it for peak-load purposes; the whole of the maximum demand charges are accepted and very little benefit is derived from the low unit charge. I can understand the author's anxiety to have all plant running on base load, but when a large interconnected system is being operated the problem of dealing with the low night loads has to be considered from the practical, as well as the economic, angle. Many of the largest machines are unsuitable for operating on a two-shift basis, and have therefore to be run through the night. The total night load is so small that the loads which can be given to these machines might be dangerously low, and any proposal to generate night load on smaller machines will only add to these difficulties.

The ideal plant for small-scale pit-head generation would seem to be quick-starting turbines and boilers working on a two-shift basis, the boilers being designed to burn the lowest grades of colliery refuse. If this plant were used for taking care of peak-load variation and if the pumping load could be concentrated into the night shift and imported from outside sources, the arrangement would probably give the greatest financial benefit to the colliery system. This suggestion does not, of course, cover the much more ambitious scheme of providing block exports from the coalfields into a national network. Such a proposal is certainly worthy of close examination but, as I suggested earlier, its consideration would appear to be outside the scope of this paper.

Mr. D. M. Rait: The substance of the paper is really a question of colliery generation versus Grid generation. Low-grade fuel at collieries generally has no market value as it probably contains up to 30% ash and has a high moisture content. Such fuel can be utilized, if efficiency is sacrificed, for firing colliery boilers; if not used in this way it has to be dumped. If the whole of the electricity supply for collieries were purchased from the Grid, the disposal of this very-low-grade fuel would present a problem.

On the question of continuity of supply, the author has dealt only with the financial aspect. What concern the colliery management are the repercussions resulting from the supply failure. A failure may involve withdrawal of the men from the pit, and where

* *Journal I.E.E.*, 1943, 90, Part II, p. 233.

Ilgner flywheel generators are employed a stop of 20 minutes will cause the flywheel set to lose so much speed that the bearings are not properly lubricated; the brake then has to be applied to the flywheel and the set shut down. Under such conditions, it may be hours before the set can be restarted and winding resumed, even though the supply has been restored in the meantime. Fortunately, this is a rare occurrence.

Can the author state what type of protection is in use on the transmission line interconnecting collieries in South Wales, a point not mentioned in the paper? One trouble experienced is with transient faults on the transmission line. It would be of interest to colliery engineers if the author would state what protective gear is used, and if it is effective.

Mr. C. O. Boyse: I should like to mention two points concerning transmission-line construction which arise out of the paper. The first is the amount of ice loading to allow for in the design of lines to be erected in a district such as South Wales. This is a difficult problem, and it is doubtful whether the solution tentatively offered by the author, to design for $\frac{3}{4}$ in of ice, instead of $\frac{3}{8}$ in, would very much reduce the chances of breakdown under the extreme conditions experienced in 1940. In fact, it seems impracticable to make provision for such severe conditions at reasonable cost.

The second point concerns the failure of the Kay poles. I believe these were erected in 1918, so that they had already survived the rigours of the climate of South Wales for well over 20 years—a good advertisement for their durability. I suggest that the author is not quite fair to this type of construction when he says that the Kay pole needs considerable maintenance. The various parts of the poles are very effectively protected against corrosion—the stays being galvanized and painted, and the tubes dipped and wrapped with hessian impregnated with bituminous compound—so that although the capital cost of Kay poles may appear to be high by present-day standards, such poles have been found to give very many years' service with little or no maintenance.

Mr. H. Watson-Jones: The question of electric power for mechanized coal-mining is becoming increasingly important, and I feel that the ultimate solution regarding national fuel economy must be sought by examining the problem from the national point of view. Without entering into the discussion of public bulk supply versus pit-head generation, it is most important to consider the economies which can be realized by complete electrification within the mine, irrespective of the source of the supply. Correlating the author's figures with the findings of the 1938 Coal Commission regarding amalgamations, collieries may in future be grouped into units with an output of roughly 5 000 000 tons per annum each with a maximum demand, if completely electrified, of between 30 000 and 40 000 kW. Such group power stations should, in my opinion, be operated by or linked to the Grid, thereby reducing standby. The progress in modern cooling-tower technique would make these stations less dependent on river sites, and enable them to be located near to the source of supply. The fact that, in 1938, the collieries burnt under their own boilers only 2 000 000 tons less than the total coal required for public electricity supply in the whole country supports the author's claim that an economic investivation should be made into the general problem of pit-head or coalfield generation.

The author's consumption figures are exceedingly valuable. The figure of 35 kWh per ton raised is on the high side against the average for the whole country, mainly because of the unique geographical features of South Wales and its high compressed-air and pumping loads. A more average figure for the whole country would be 25 kWh/ton, while figures as low as 17 kWh/ton have been quoted. His estimate, on a heat-consumption basis, of 0·7 million B.Th.U./ton raised for all-electric operation appears very conservative. Taking an average of 25 kWh/ton for the whole country, and an average heat consumption of, say, 15 000 B.Th.U./kWh in a modern power station, we get 0·375 B.Th.U./ton raised, which is half the author's figure. This, of course, neglects transmission losses and assumes that the generating station is close to the colliery group. In 1938, the collieries burnt 11·86 million tons under their own boilers to raise 227 million tons of coal. Assuming a calorific value of 10 000 B.Th.U./lb, this gives 1·17 million B.Th.U./ton raised, compared with the author's figure of 0·7. Adding the fairly considerable amount of electricity imported as bulk supply, the figure is higher still. These figures indicate that more than half the coal at present consumed at the collieries might be saved by complete electrification if the generating plant were centralized into large, modern, efficient generating units. It is accepted that large stations could be designed for efficient high-pressure steam generation using the low-grade fuels available on the spot.

A complete change-over to all-electric operation of colleiry plant would, however, mean scrapping much serviceable boiler plant and other equipment, and as an interim measure consideration might be given to coal winding by the turbine-electric equalized system utilizing Ward–Leonard d.c. electric winders in conjunction with motor generators equipped with flywheels and driven by geared turbines, thus removing the peaks from the existing boiler plant and extending its useful life. In any case, an investigation would show that by complete electrification of all collieries with grouped power supply, the annual saving in fuel alone should more than provide for interest and capital charges for such a conversion, if carried out on rationalized national lines.

Mr. C. J. O. Garrard: The author has said that South Wales may become a centre for the export of electrical power. I believe that this will happen to such an extent as to make some of the assumptions on which the paper is based no longer applicable. The only way to meet the expansion of the country's demand will be to build large generating stations in such areas as South Wales and the North-East Coast, where water and coal are plentiful. We may then see 2 to 3 million kW being exported from South Wales; this amount makes the author's figures of about 250 000 kW as the possible maximum demand at all the collieries in that district appear small. There will be a profound effect on the supply of electricity to the mines, since the power they will consume will be only a small percentage of the power generated in the district. Pit-head generation will decline, and the economic utilization of coal and of coal heat will become still more important than it is now.

The electrification of an area such as South Wales cannot be considered apart from the general social and regional planning of the district. If we are going to generate in South Wales on a very large scale, general industry must also be developed, for the sake of regional balance, to utilize waste heat from the power stations, and possibly also the by-products from the coal. Many dirty and ugly colliery installations will have to be removed; existing stations will have to be replaced by a few large, clean, well-designed plants to which coal might be transported by means of conveyors.

I should like to have the author's long-term views on colliery switchgear. Does he think that 25 MVA and 3·3 kV will remain the maximum for use underground and, if so, for how long? Coal faces are continually advancing, and it is only a matter of time before faces in adjacent collieries must meet; is there any possibility of interconnection underground, using voltages higher than 3·3 kV? Is there any future for air-insulated gear underground in preference to oil circuit-breakers, for example?

Earth-leakage protection is a very thorny problem, and to obtain selective and rapid operation seems very difficult. Recently, I and my colleagues have discussed whether more use could not be made of the voltage-operated type of earth-leakage relay by sub-dividing the earth continuity into zones and putting one relay in each zone.

If earthing of feeders has to be done regularly, proper apparatus should be employed. We have recently developed a mining unit for 3·3 kV or 400 volts to comply with the new draft regulations; in this an internal switch is used to disconnect the circuit-breaker from the busbars and connect it to earth so that the feeder may be earthed through the breaker.

Mr. J. R. Harding: The design of cross-arm in Fig. 9 is certainly effective in providing torsional strength to resist unbalanced conductor tension, and lateral strength to enable the greater working load capacity of post insulators to be developed, but I should not have thought that the author would prefer a long-span construction such as this for the severe conditions with which he has to contend. According to the figures in the paper, the hot sag in the first case is about 9 ft and in the second about 3 ft, and the amount of additional ice load which the conductor could stand without failure would be nearly double with the shorter span construction as shown by Table 5. If the conductor does not break, the increased strength of the cross-arm is not necessary, and if it does break, something must fail at the nearest support, unless every support is designed to withstand all conductors broken, which is impracticable on the grounds of cost. If, therefore, the binder does not break or slip, either the pole foundation will yield or the pole itself will break. In the case of rock foundations the latter possibility is quite real, and it would surely be easier to replace a broken cross-arm than to obtain a new pole and erect it under severe weather conditions. I should provide the extra reserve of strength required by using spans of about 250 ft, as in the second case, and adopt a reduced conductor tension which, on the short spans, would make a broken conductor of 0·15 in² section a very remote contingency.

I note that in the cost comparison in the Appendix the cost of erection of the intermediate poles is assumed to be the same for each alternative, and the same size of foundation baulk is used. When adjustment is made in these and other minor respects, I find that the cost of the shorter span construction works out at about £1 085 per mile, on the basis adopted by the author, so that the long spans would appear to show no very great saving.

The fitting in Fig. 9 has one minor disadvantage in that it is welded before being galvanized, which always involves the risk of discontinuity of the galvanizing due to scale or impurities occluded in the welds. I can confirm that the method of attachment to the pole by means of two bolts and a vertical channel with the toes against the pole is very simple and satisfactory, as I have used it for many years.

Mr. H. Willott Taylor: Mr. Andersen deprecates the use on the mountains in South Wales of the single-pole pin insulator design of 33-kV line recommended by Mr. K. L. May and myself in our paper recently read before The Institution. So do I. Our paper suggests the alternative of a wooden H-pole, suspension type of line with horizontal conductor formation for higher altitudes or other similar arduous conditions. This is the type of line I would prefer to employ in the circumstances envisaged by the author, especially where continuity of supply is of vital importance. I suggest that rather than spend more money on making the cross-arm very strong (far too strong, in fact, for the wooden pole on which he puts it) the author would be wiser to spend a little more in putting up a good H-pole suspension line and so make the supply to his collieries even more secure.

I sympathize with him on his unfortunate experiences with ice loading in 1940. Under such exceptional conditions, in which it is economically impracticable to try and forestall with certainty every possibility of failure, we have found it to be an advantage to have a cross-arm which is somewhat of a weaker link. It is easier to replace a few cross-arms than a series of broken poles.

A suggestion is made that the Regulations might be modified, but I do not think this is necessary. The present Regulations are intended to be a minimum and should be treated as such. The parts of the country where particularly arduous conditions may be expected are within the jurisdiction of undertakers who can be relied upon to do as the author has done, namely to adopt higher factors of safety.

As a rule ice loading seems to be either negligible or very heavy. Under these conditions, I agree with Mr. Boyse that to design for $\frac{3}{4}$ in ice, instead of $\frac{5}{8}$ in, would contribute very little towards taking care of heavy loading conditions.

Line-post insulators have been used for many years in preference to the ordinary pin type on the 33-kV lines in Cornwall and South Wales, where salt or industrial deposits are experienced, and they have proved very satisfactory indeed.

I agree with Mr. Harding about the author's estimate of the comparative costs. I consider a straight cross-arm giving horizontal conductor formation would be cheaper and preferable to the author's cross-arm involving a triangular formation of conductors.

Mr. K. Dannenberg: The author refers in Section 9.1 to earth-leakage protection and switch- and fuse-gear. I presume he is aware that earth-leakage protection for switch-and-fuse gear has recently been developed quite successfully in the form of a small striker device which is sensitive enough to operate in conjunction with a core-balance current-transformer circuit. It resembles a fuse which operates a striker in consequence of the current setting of a chemical charge, and operates either mechanically against a trip bar or electrically against an auxiliary contact. This arrangement was originally developed in conjunction with fuse gear for the prevention of single-phasing. Reference has been made to the disadvantage of fuses for back-up protection in not being able to give such single-phasing protection, but I know of several types of switchgear on the market incorporating striker fuses which prevent this.

Mr. P. B. Frost (*communicated*): It appears from Fig. 7 that a single earth-electrode system is used for earthing all metalwork associated with the h.v. system as well as the neutral of the l.v. system. This practice has for some years been regarded as dangerous, because an earth fault on the h.v. system is capable of raising the voltage of the earth-electrode system so much that apparatus on the l.v. network (which extends far beyond the resistance area of this earth system) will break down to earth proper. Such occurrences are on record, particularly where the resistance to earth of the earth-electrode system is not very low.

The spacing of 30 ft between the cast-iron pipes is probably great enough to avoid any appreciable overlapping of the resistance areas and so provides an economic layout for the earth-electrode system. A test of the resistance in the manner indicated would not, however, give the true values of the separate earth electrodes, nor give a measure of the resistance of the three electrodes in parallel. To measure the separate and combined resistances it would be necessary to have an auxiliary testing earth-electrode at a much greater distance than 30 ft. Once the earth-electrode resistances had been determined, measurements between the three pairs of electrodes would give a ready check that no marked change in the condition of the electrodes had taken place.

Mr. R. Larkworthy (*communicated*): The pole-top fitting described by the author seems to me a very workmanlike and robust design and reasonably neat and pleasing. Using proportionally strong poles, the fitting gives rise to a very strong construction which with the longer spans enables overall econo-

mies to be made. I consider many existing designs of cross-arm very flimsy, particularly in the direction of the line.

Mr. H. Pritchard (*communicated*): I have seen the pole-top fitting described in the paper in use and am bound to say that it looked a very good job. Furthermore, the linesmen, who have had much experience of many types of construction and fittings, were loud in their praise for its simplicity of fixing and great strength. Naturally, to match its strength stronger poles than usual have to be employed, so that in one example a 55ft stout pole may be cut down to 38 ft to obtain the necessary thickness. The sawn-off pole tops are cut into suitable sizes for use as kicking blocks. The resulting construction gives an economic span length of about 525 ft with maximum spans up to about 650 ft. It was noticeable after the 1940 ice storm that hundreds of cross-arms of the relatively flimsy character largely in use were twisted and distorted in positions where a stronger fitting would have sustained no damage; it took several weeks of work to straighten or renew them and re-bind the conductors.

DISCUSSION BEFORE THE WESTERN CENTRE, AT CARDIFF, 13TH MARCH, 1944

Mr. L. Howles: The author forecasts a very heavy increase in demand for electricity supply in the coalfield, and as and when this develops the power-generation resources will obviously have to be expanded. He suggests that, in order to fulfil the requirements of the colliery load, a proportion of power should be generated at several of the larger collieries or in the centre of groups of collieries. There is much to be said in favour of coalfield generation, but this must not necessarily be pit-head generation. As and when substantial increases in generation resources are required, it is obvious that the load requirements of the collieries as well as of other industries and public services should be reviewed. The site for the power station should therefore be chosen to achieve the lowest cost at the consumers' terminals consistent with security of supply and the national requirements on the Grid system, all of which can be done if development is carried out by authorized undertakers operating under present legislative powers and controls. If, however, colliery companies' generating plants are to take their place in the national system, many financial and economic problems will arise that can probably only be resolved by legislation.

The operation of transmission systems by colliery groups, where the power lines cover territories already covered for other purposes by the statutory undertaker, is uneconomic. Much progress has, however, been made by agreements between the parties for the interconnection of systems, mutual standby facilities and the like, which, if pursued, will largely remedy the wasteful use of capital that is inevitable in non-co-operation.

To reach rapidly the ideals that the author has in mind, it appears necessary for owners of non-statutory generating stations and transmission lines to accept a substantial measure of control, although the same effect, based on experience, will probably be achieved by agreement as and when opportunities occur; but that process is inevitably slow.

Mr. J. F. Smith: In considering electricity supply development in South Wales, account must be taken not only of the admittedly important colliery loads, but also of other substantial public-service and industrial requirements. The area to the north of the coalfield is very barren from an electrical point of view, but to the south and between it and the coast-line there are large concentrations of population and industry, particularly in the main coastal towns. Location of generating stations to serve the area would therefore be governed by the relative costs of transmitting energy by electric lines or in the form of coal. The following example indicates that only under certain conditions of load factor would such stations be ideally located at pit-heads.

The coastal concentrations of electrical load are each about 15 miles distant from colliery centres where generating plant might conveniently be installed; to deal with such loads electric lines capable of delivering about 60 000 kVA with adequate margin of standby would be necessary, this capacity allowing for some further development. Assuming that both generation and distribution was at 33 kV, the transmission system would probably comprise three separate 66-kV 0·2 in^2 electric lines, 15 miles long, each complete with 30 000-kVA step-up and step-down transformers, there being one complete line standby to two operating lines. The total cost, including 33-kV switchgear of suitable rupturing capacity, substation sites, buildings, concrete foundations, pilot cables, etc., would be about £210 000, and allowing 12½% to cover interest, depreciation, rates, maintenance and the relatively small running costs the annual charges would be £26 250 per annum. Assuming 0·85 power factor, although experience shows a higher figure might well be achieved, the load delivered would be 51 000 kW, and the capital charges for transmission reduced to a cost per unit delivered would vary from 0·047d. at 30% load factor to 0·0141d. at 100% load factor.

The cost for delivering fuel over the equivalent distance is at present approximately 4s. per ton, and at 1·2 lb of coal per unit sent out—being a performance easily reached by a modern generating station—the cost of fuel transport becomes 0·0257d. per kWh. For the conditions assumed, it would thus be cheaper to transmit electricity than convey the energy in the form of fuel provided the load factor was 55% or higher. With transmission over 20 miles, the corresponding load factor limit becomes 50%.

Possibly the development of off-peak industrial loads, water and space heating, etc., may produce load-factor conditions in excess of the above limits, but unless this is the case it appears more economic to transmit energy in the form of fuel from the coalfield to the coastal areas, rather than to generate at pithead and transmit via electrical lines. This conclusion is based on the assumption, which experience shows to be a reasonable one, that generating plants can be constructed and operated with high efficiency equally well in the colliery areas as in the coastal towns.

The author claims a probable saving by connecting colliery generating plant to public supply, if the colliery plant deals with the base load and public supply with the morning peak. The saving claimed is based on two assumptions which are open to criticism, i.e. that the morning colliery peak load is off peak compared with other industrial and public-service load, and that public supply would provide 88 200 kW of capacity without any maximum demand charge therefor. In South Wales electrical supply for industrial needs and domestic cooking has developed to an extent that maximum loads on generating stations occur in the morning and the colliery load cannot be considered as off peak. It does in fact contribute to the highest demand on the generating plant resources, and must therefore bear its proportion of the capital costs of such plant.

Mr. J. W. Dorrinton: I agree with Mr. Howles that interconnection of private generating plants with public supply systems would save much duplication of transmission lines, but I am surprised at the confidence with which he views the possibilities of such a scheme. It must be remembered when dealing with main transmission lines, particularly those of the C.E.B., that the short-circuit powers involved are very high, often 1 500 MVA, which is far in excess of the capacity of the switchgear of a private power plant. It also appears from the paper that the small station would take the highest load factor, and that its peak would almost coincide with the public peak. Thus these stations will not be of very great value from a load point of view, and the public authority could hardly be expected to provide the higher capacity gear to reduce the short-circuit MVA.

On the other hand, the number of units sold per annum would not be very large, and the private company would hardly find it economical to install the gear themselves. In my experience, where a large undertaking fringes on areas supplied by smaller concerns, such interconnection is not easy for other reasons. These difficulties are partly due to differences in transformer connections producing small permanent phase-angles between systems where these already have a common point of connection, such as the Grid, even if very indirect. In new plans, no doubt these troubles could be avoided, but in many cases matters have gone too far for this.

I agree with Mr. Howles that legislation is far better avoided, but I foresee difficulties with load dispatching unless compulsion be applied. Load dispatching would have to be controlled from a central office, and private companies might not obey orders that were unprofitable or inconvenient.

Mr. A. W. Kidd: In Section 5.1 the author gives an impressive list of advantages, which cannot be ignored. I disagree with the second disadvantage, as with good modern steam conditions and using a reasonable-size generator the efficiency should be almost equal to that of selected stations, taking into account the transformation and transmission losses the selected station has to carry in delivering power back to the pit-head. The saving in freight and coal-handling charges stated should therefore be counted as pure gain, and I should like to see Section 5.2 revised in this light.

I favour what might be called the unit scheme for colliery generation on the lines shown in Figs. 4 and 5, except that perhaps Fig. 5 shows a particular rather than a general application. I would prefer to substitute Fig. A, which shows that the scheme

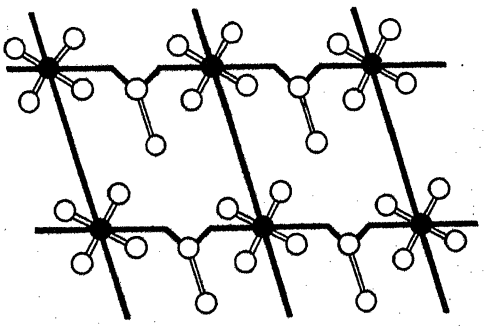


Fig. A

33-kV line. 11-kV line.
● Colliery with generating plant.
○ Colliery supplied from system.

is universally extensible and could be made to cover the whole of the South Wales coalfield or any other coalfield with similar conditions. The symmetrical arrangement of collieries shown is, of course, quite hypothetical and would in practice be varied to suit the actual geography.

At collieries with generating plant there would be, say, one 15 000-kW set generating at 11 kV, and one step-up transformer which normally would export into the 33-kV system the surplus power left after supplying the colliery itself and the adjacent collieries fed from the 11-kV board. This transformer would be capable of taking the supply from the system if the generator were shut down for any reason, and it will be seen that it need not be equal in capacity to the generator, as it has to deal only with surplus power or the sum of the actual loads at the collieries, whichever is the greater.

Preferably, there would be two 80 000-lb/hour m.c.r. boilers at each colliery arranged for pulverized-fuel firing, and conveniently there could be incorporated in the boiler flue leading to the stack a cylindrical horizontally-inclined rotary dryer controllable by dampers and a by-pass flue for drying washery slurry to enable it to be efficiently pulverized and burned. The boilers should be specially designed to allow frequent starting-up and shutting-down without damage.

The number of generating sets dotted about the system would be chosen to allow one set out and the remainder to carry the system load when running at their economic rating. The margin between economic and maximum continuous rating could be a safeguard to allow for trouble to a further set under these conditions. A leading factor in choosing the site of a unit would be the presence of a washery at the colliery, as it is normal practice for one washery at the more important colliery to serve adjacent collieries.

The size of 15 000 kW was found from a study of the problem, in relation to a particular large group of collieries, to be the optimum capacity, the sets having an economic rating of 12 500 kW.

The main transmission lines could conveniently be single-circuit 0·15 in^2 of the type advocated in Section 12; and this arrangement would keep the capital cost down to a reasonable figure. Heavy double-circuit lines would not be required, as the transmission network normally only carries small blocks of power. The arrangement gives the maximum security of supply.

To ensure the desired direction of power flow in the network one quadrature regulator would be required in each closed ring in the line normally carrying the least load, and preferably the main 11/33 kV transformers should have on-load tap changing. At the collieries without generating plant, where the 33-kV lines are looped-in, a five- or six-panel 33-kV switchboard with bus-section and two or three step-down transformers would be required.

With such a scheme the amount of spare and standby plant is reduced to a minimum. One spare turbine and alternator rotor and one spare 11/33-kV transformer at a suitable central spot would be the principal gear required.

Mr. D. A. Picken: The author's analysis of the proposed distribution of load between pit-head generation and public supply is presumably based on economic merit, and similar figures for load sharing would be interesting, where the normal public supply is based on a true economic basis, rather than on the load-development basis at present utilized. The tendency now is for the maximum-demand charge to be low and for the unit charge to be higher than is justifiable, e.g. Bellamy in 1936 estimated the fixed charge for his generating station alone to be almost £4 per kW of maximum demand. Since that time, the tendency has been for considerable increases both in the capital value of the plants and also in the cost for a given type of equipment. If these figures were applied to current tariffs, it would cause a marked increase in the maximum-demand charge and possibly some decrease in the unit charge.

Regarding the author's cross-arm design, I suggest that the cross-arm shown is very much stronger than a single pole; in the event of a conductor breaking under wind pressure the pole would almost certainly be fractured, and this seems to me merely to move the fault to a more inconvenient portion of the distribution system, as obviously the pole is much more difficult to replace than a cross-arm.

Mr. David J. Thomas: The suggestion of using a B.Th.U. basis for comparing electric and steam supplies to collieries is a valuable one, and should be extended to provide a general basis of comparison instead of the present indeterminate method. For instance, in Section 3.1 it is stated that 1 kWh can be generated from 1·5 lb of coal. Coal is a generic term, and to tie rigidly a very elastic commodity to a precise unit and deduce from the results a basis of comparison cannot mean anything. It is time

that the expression "so many pounds of coal for so many units" was changed to "so many units for so many B.Th.U.'s" and this then related to pounds of coal, if necessary.

Earthing to outgoing feeders will soon be obligatory, and the only satisfactory provision for this is to make the earthing facility an integral part of the switch. This will ensure "the efficient and easily applied earthing" as rightly called for by the author; both visible isolation and earthing should be available. It is also preferable that the earth circuit be finally closed through the main switch and not through an auxiliary switch. Flame-proof switchgear embodying all these desirable features is already on the market.

Standardization in electrical equipment is to be welcomed as an ideal, but so far the problem has not been dealt with seriously. One reason is that every maker seems to want the others to standardize on his standard. The author should consider this, because he refers to the 0·55-kV system, which is not a standard voltage. The collieries can alter this without reference to external bodies, as there is no real obstacle to be overcome; this is confirmed by at least one large colliery company, which has successfully adopted a 400/440-volt standard.

Mr. A. B. Price (*communicated*): A major problem confronting collieries is the disposal of dust and slurry, which is more troublesome in South Wales than probably in any other coalfield, on account of the dusty nature of the coal. Conditions are further complicated by some power stations specifying that the amount of fines below $\frac{1}{8}$ in must not exceed 40% of the boiler fuel. This means that, in some instances, the nature of the coal is such that only a very small percentage of $-\frac{1}{16}$ in can be left in the fuel.

Fine coal can be divided into super fines and coarse fines. The former is usually slurry or aspirated coal below about $\frac{1}{2}$ mm, and the coarse fines can be defined as coal below $\frac{1}{16}$ in, which is usually screened from the raw coal going to a washery. The percentage of these fines varies from coal to coal, but representative figures are $\frac{1}{2}$ mm × 0, 4 to 6% of the run of mine coal, and $\frac{1}{16}$ in × 0, 10 to 13 %.

Washeries are usually built on a site easily accessible to the pits and with an ample water supply; both of these conditions also apply to generating stations. If the fines are clean enough they can be sent to pulverized-fuel-fired boilers without further treatment; otherwise they must be treated separately in the washery to reduce ash and moisture to economical limits, and the clean product then conveyed to the boiler bunkers. But if this coal has to be transported to another power station some distance away, then the cost per ton will, under present-day tariffs, have to be increased by 2s. 3d. per ton to carry it 8 miles and 4s. 2d. per ton over 16 miles. Further the ash problem would be reduced to a minimum as it could be easily disposed of with the washery refuse.

I feel that such a scheme would have far-reaching results, as not only would the collieries and districts in their area benefit, but also those large stations at some distance away from coalfields and using chain-grate stokers, since the collieries could supply them economically with reasonably dust-free coal.

Mr. W. Todd (*communicated*): The author has stressed the need of standardization of industrial electrical equipment. This, I believe, can be achieved only by the combined and persistent demand of users. Two standards, namely for heavy duty and normal duty, appear desirable, and specifications should cover all essential details governing interchangeability and reliability.

For motors, I suggest the following range from $\frac{1}{4}$ h.p. to 200 h.p.: $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{2}$, 2, 3, 4, 5, $7\frac{1}{2}$, 10, $12\frac{1}{2}$, 15, $17\frac{1}{2}$, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 125, 150, 175, 200 h.p. Standardized details should be: (*a*) Centre height of shaft, distance from *inner* end of coupling seating to fixing holes in all directions; (*b*) shaft diameter, keyway and quality of steel to be used; (*c*) dimensions of bearings; (*d*) minimum weight for specified horse-power, to ensure stability of structure; (*e*) life of conductor and covering, position of terminal box, size and method of arranging connecting terminals; (*f*) temperature rise in still air; (*g*) voltages. Separate standards are needed to cover screen-protected, totally-enclosed and surface-cooled types.

Switchgear presents more difficulty, but it should be possible to cover structural dimensions, temperature rise of connections, contacts, etc., without interfering with individual characteristics.

If a conference of electrical engineers, manufacturers and designers could reach agreement on certain standards, the change-over should not be unduly difficult with fabricated structures.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. B. L. Metcalf (*in reply*): The subjects discussed fall under three main heads: (*a*) choice of switchgear and interconnection with grid, (*b*) pit-head generation, and (*c*) overhead line construction. It is proposed to reply to the various speakers under these heads.

(*a*) *Choice of Switchgear.*

Mr. Cluley questions some of the calculations for short-circuit capacity. The first example assumes incoming feeders to the 33-kV busbars and direct transformation to 3·3 kV with two 3 000-kVA transformers, each having 7·5% reactance, in circuit. This gives the figure of 69 MVA with which Mr. Cluley agrees, although he appears to have made slightly different assumptions. With regard to the arrangement shown in Fig. 4, it has been assumed that the generator would have 15% reactance and the 15-MVA transformer 7·5%. Assuming again a figure on the 33-kV busbars from outside sources of 500 MVA, this gives 268 MVA as shown in the paper. Assuming 6 000 kVA of transformer plant at 7·5% reactance between the 11-kV busbars and the 3·3-kV busbars, this gives 61 MVA on the 3·3-kV busbars, to which must be added the synchronous plant. The reason the short-circuit value on the 3·3-kV busbars is less with the layout including a generator, is that the 500 MVA assumed on the 33-kV busbars is choked through two transformers in series before affecting the 3·3-kV switchgear.

It is surprising to note that Mr. Cluley considers 75 MVA too high for the average colliery scheme. The object of the proposals contained in the paper is to exclude the use of reactors, except for the pit feeders, and to improve the breaking capacity of the switchgear in general use. With regard to limiting this value to 25 MVA by inserting reactors in the pit feeders, the reactors are usually installed with a current-carrying capacity equivalent to that of the pit feeders; it will be seen from Table 3 that the percentage-reactance figures are not excessive.

Mr. Cluley's interpretation of Clause 14 (iii) of the "Report of the Committee on the Amendment of the General Regulations Governing the Use of Electricity in Mines under the Coal Mines Act, 1911" seems unnecessarily wide. The prevention of the exposure of live conductors is only called for on apparatus used at or within 300 yards of the coal face and in any other place where the representative firedamp content in the general body of the air exceeds 0·5%. In these situations the voltage is usually less than 650 volts, and, owing to the reduced short-circuit current to be dealt with, air-break switchgear which complies with 14 (iii) can be used. It is certainly unfortunate that the colliery industry must pay for the complete re-design of the range of flame-proof oil circuit-breakers manufactured by five or six firms, owing to the interpretation which is being put on this draft regulation. One design of switch produced by the leading manufacturers in co-operation with the users would have saved

much drawing office and development expenditure, particularly in view of the inelastic demand for such a switch.

For deep shafts with workings far inbye, the use of 6·6-kV switchgear mentioned by Mr. Garrard would be of considerable advantage. If 6·6 kV is introduced underground this should become the standard voltage for the whole colliery to the exclusion of 3·3 kV. This means the adoption of 6·6-kV reversing contactors for winders (a problem which has been satisfactorily solved) and of flame-proof 6·6-kV reversing contactors for haulages, no designs for which yet exist. The ever-increasing size of coal-cutter motors and the advent of power loading are increasing distribution problems underground. It is unlikely that interconnection between collieries underground is likely to be adopted. Cables should not be left in disused roadways or installed in places where they are inaccessible for repair.

The adoption of air-insulated gear underground is largely a matter of space. The ideal is to eliminate oil, but the mining-type flame-proof switch with compound-filled busbars is compact, easy to handle and easy to install. There is no lack of provision for earthing the outgoing feeders with this type of switchgear. This problem has not been given the same degree of attention, however, on the larger draw-out circuit-breakers used on the surface, and it is this type of gear to which attention is drawn in the paper.

Mr. Thomas is perfectly justified in criticizing the mining industry for its arbitrary choice of medium voltage. The reason for not adopting the standard voltage of 400 was to economize in cable sizes underground. Take a 100-kVA transformer underground supplying a double-unit face. The transformer must start 300 yards from the coal face, and assuming that it will not be moved up until the face has advanced 300 yards, a length of 600 yards of medium-voltage cable plus, say, 100 yards of trailing cable must be allowed for, and this cable must for the last length be flexible to enable the gate-end boxes to be advanced. The size of cable must be kept down without excessive voltage drop.

The mistake made was in the wide variation of voltages selected, such as 625, 600, 550, 500, as well as 440 and 400 volts. 500–550 volts is probably the most common.

B.S. specifications do very little to further standardization, as Mr. Todd points out. They lay down standards of performance for motors, without insisting on standardization of physical dimensions. Adoption of the standards recommended by Mr. Todd would be of enormous advantage to the mining industry, as well as to manufacturers.

Mr. Rait asks for information on the subject of protection. This is outside the scope of the paper, but it may be said that the ideal system of protection is probably one involving pilot wires, although their maintenance is an added burden on the maintenance staff. The usual practice in South Wales is directional overload and earth-leakage protection where there are not too many interconnected rings to complicate the directional feature. Where that condition does arise, plain overload and earth-leakage is adopted.

Mr. Frost is correct about the potential danger of earthing the metal-work of the h.v. system to the same earth electrode as the neutral of the l.v. system, if the resistance to earth of the earth-electrode system is not very low. The importance of keeping this value low is appreciated by most colliery electrical engineers, and the method of testing illustrated is, as Mr. Frost says, to keep a check on the condition of the electrodes rather than to measure the combined resistance.

If it is true, as Mr. Dorrington points out, that there are difficulties associated with the interconnection of an industrial generating system and the Grid. Usually interconnection would be indirect, i.e. it would be through the system of the local authorized undertaker at a lower voltage and prospective short-circuit value. In South Wales the power companies' network is operated for the most part at 33 kV with certain lines at 66 kV; it was as the result of practical experience of interconnection with this system that the value of 500 MVA at 33 kV was selected. The flow of power through the system could be controlled by quadrature boosters, as Mr. Kidd suggests.

Mr. Picken points out that the tendency is for the maximum-demand charges to increase and for the running charges to decrease. This focuses attention once more on the load factor and emphasizes the need for using all means for improving the load factor such as, for example, transferring the pumping load to the back shifts. The connection to the same generating system of industries whose peak demands do not coincide, also becomes increasingly important.

(b) Pit-Head Generation.

This is bound to remain a controversial issue until it has been thoroughly investigated on purely technical grounds, bearing in mind the importance of certain factors which did not affect the issue in the past. These are the amalgamation under one control of collieries in one region; the increasing mechanization and consequent high potential demand for electric power; and the increase in the percentage of coal washed, with the resulting problem of the disposal of fines, aggravated by the introduction of water infusion for dust suppression underground.

The paper deals with the question of pit-head generation in relation to the economics and security of power supply to collieries, and only indirectly in relation to the effect on the supply problem for the region as a whole. Mr. Rait has misinterpreted the issue in stating that the substance of the paper is a question of colliery generation versus Grid generation. The attempt is to show the proper relationship between colliery generation and Grid generation.

Mr. Smith shows the same misunderstanding in his anxiety to prove that, for a distance of 15 miles, it is cheaper to transmit electricity than to transport coal. The sites chosen for the two selected stations in the power company's area in South Wales could hardly have been better chosen in relation to load density, coal supplies and water. But applying Mr. Smith's figures in reverse, and assuming that a group of collieries taking 51 000-kW maximum demand was situated within 15 miles of the selected station, and that the load factor was 50%, the cost of fuel transport to the selected station would be 0·0257d./kWh, and the capital charges on the transmission lines, etc., returning the supply to the collieries 0·0282d./kWh, making a total of 0·054d./kWh. This seems to bear out the contention that for a large group of collieries pit-head generation is amply justified, as the above fuel transport charges and transmission charges would be saved. To quote Mr. Howles: "The site for the power station should be chosen to achieve the lowest cost at the consumers' terminals consistent with security of supply and the national requirements on the Grid system." For colliery consumers, the right place for the generating station would appear to be at the pit-head or adjacent to central coal-washery plants. This does not mean that interconnection between collieries would be eliminated, as suggested by Mr. Horsley, but that the vulnerability of the hill-top transmission lines would be counteracted by the strategic location of a number of unit generating stations. Based on considerable operating experience, Mr. Pugh substantiates the claim that these stations could be run just as efficiently as selected stations.

The economic justification for colliery electrification is corroborated by the interesting figures given by Mr. Watson-Jones. His main criticism is that the figures in the paper are too conservative. Other speakers, too, suggest 1·2 lb of coal per kWh

instead of 1·5. The choice of conservative figures was deliberate to avoid the charge of over-stating the case. No doubt in a highly electrified area, such as the North-East Coast, and assuming a thermal efficiency of generation of 25%, the heat consumption per ton of coal raised would be below 0·5 million B.Th.U.

Where all the underground operations are performed electrically, there is a potential saving of 12 kWh/ton out of the total of 35 kWh/ton, or 6d. per ton raised at 0·5d./kWh.

Mr. Horsley illustrates by his figures that the high power consumption per ton of coal raised in South Wales is due, more than to any other factor, to the relatively low consumption of electricity for coal-face operations, such as cutting and conveying. Owing to the ubiquity of compressed air underground in South Wales, air picks can be used in many places instead of cutters, and this accounts to some extent for the low relative percentage of coal cut by machinery.

Mr. Price brings out a very important point in drawing attention to the conditions imposed by certain purchasers of coal for selected stations, who limit the percentage of fines below $\frac{1}{8}$ in. He quotes a representative figure of 4 to 6% of run-of-mine coal as being dust of a size below $\frac{1}{2}$ mm. This dust alone would supply almost twice the electrical requirements of the collieries themselves and would probably have an ash content not exceeding 16%. The effect of water infusion is likely to reduce the amount of dry dust available, and with Chance washeries will necessitate wet screening, with the possibility of subsequent drying of the slurry produced to make it suitable for pulverized-fuel firing.

Two speakers—Mr. Cooper and Mr. Kidd—mention the necessity of giving more attention to boiler design to enable the plant to withstand the temperature variations caused by frequent shutting-down and starting-up. This is important, and the same applies to some makes of generators which seem unable to withstand such conditions without distortion of the insulation. As Mr. Cooper points out, boilers can be designed to burn coal down to 3 000 B.Th.U./lb, but whether the labour costs justify the burning of such low-grade fuel must be determined in each case. The tendency in this country among progressive colliery undertakings is to up-grade their fuel even when burnt at the pit-head, rather than pass a large percentage of rubbish through the boiler plant. In Section 7.3 the coal price and calorific value used are the usual reference data for calculating coal clauses. As the worked example is a comparison only, the price of coal is not important. Mr. Cooper must be aware that power companies, by the operation of the coal clause, over-insure themselves against high coal prices and low calorific values.

(*c*) *Transmission-Line Construction.*

It is gratifying to learn from Mr. Andersen that the replacement cost of the post-type insulators for the single-circuit transmission-line design advocated in the paper is such a low figure. The cost of transmission lines should obviously bear some relation to the importance of an outage, and Mr. Andersen's emphasis on designing to an outage cost is interesting. The financial aspect of an outage has been stressed in the paper, and perhaps insufficient emphasis has been placed on the more serious consequences of an outage to the safety of the men underground.

It would, of course, be uneconomic and impracticable to attempt to design an overhead line to meet an ice storm similar to that which occurred in January–February, 1940. But to grade the ice loading for which a line is designed in relation to altitude, seems to be a step in the right direction. It is a practice which is adopted in most countries where ice is a source of trouble. No wood-pole transmission line is designed to hold a broken conductor loaded with ice, but the construction illustrated in the paper would hold a broken conductor in fair weather, which is unusual for single wood-pole lines.

A point which Mr. Harding and Mr. Willott Taylor have overlooked—possibly because it is not made sufficiently clear in the paper—is that the wood poles selected for the proposed line are considerably stronger than those selected for lines with shorter spans. Extra-heavy poles have been chosen (and their cost is included in the Appendix), and where the length has in consequence been too great the top of the pole has been sawn off and used for kicking blocks.

With the normal design of cross-arm, the breaking strength of the insulator spindle of the standard pin-type insulator is 1 000 lb, whereas the cross-arm will become permanently deflected if the pull in the conductor exceeds 500 lb. This seems to be carrying the weak-link idea too far. A more rational design has been attempted in the cross-arm illustrated in the paper.

Tests were made on two designs of cross-arm, and a comparison of the two is given below for a span on level country.

	Normal pole-top construction	Strong pole-top construction
Conductor	0·15 in²	0·15 in²
Span length	300 ft	535 ft
Erection tension at 60° F	3 020 lb	2 560 lb
Erection sag at 60° F	2·23 ft	8·8 ft
Weight of ice to break lb/ft (Table 5)	4·9	2·9
Length of pole required	29ft 6 in	37 ft
Pole cut from	30 ft stout	50 ft stout
Length of pole out of ground	23 ft. 6 in	31 ft
Pole diameter 5 ft from butt	10¾ in	13¾ in
Pole strength — bending moment (C.R. Handbooks, vol. II)	79 180 lb-ft	165 900 lb-ft
Pull at pole top to cause breakage	3 371 lb	5 346 lb
Insulator spindle breaking strength	1 000 lb	2 800 lb
Working load on insulator (F.S.2·5)	400 lb	1 120 lb
Strength of cross-arm in direction of line	500 lb	over 2 800 lb

From these figures, it will be seen that in the first case the weakest link is the cross-arm, and in the second case the insulator. Mr. Harding generalizes when he states that either the conductors will break and the whole line will come down, or the conductors will not break so that there is no object in increasing the strength. This may be true on level country with even spans. But on hilly country and with uneven tensions, ice on a conductor may easily twist a cross-arm without breaking the conductor, if the cross-arm can withstand only a 500-lb pull. With the new design, such conditions are guarded against. No trouble should be experienced until the conductors break under ice loading.

The simplicity of Mr. Willott Taylor's H-pole construction with suspension insulators and the excellence of the design are appreciated. To cheapen the cost of colliery transmission it is felt that there is room, however, for a single wood-pole line construction, and an attempt has been made to design such a pole, cross-arm and insulator with a more rational relationship between the strength of the various parts than is usually the case, and then to take advantage of the stronger construction to increase the span length.

THERMOPLASTIC CABLES*

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SUMMARY

The paper reviews the circumstances which have led to a considerable increase in the use of thermoplastic cables within the last few months. It points out that the relative importance of such cables cannot yet be evaluated on a peace-time basis since the economic level cannot be established and since a further competitor of natural rubber, namely synthetic rubber, is now making its appearance. In order, however, to establish a basis for evaluation it is desirable to have a thorough understanding of the general characteristics of thermoplastic cables; this is attempted in the paper with particular reference to p.v.c. (polyvinyl chloride) cables. Indications are given of the polymer situation, the definition of a thermoplastic material and the resulting implications. The building-up and testing of p.v.c. compounds is studied, and the manufacture, characteristics and uses of cables derived therefrom are considered in detail. A brief survey of thermoplastics other than p.v.c. is followed by a comparison of p.v.c. with rubber.

(1) INTRODUCTION AND SCOPE

The use of thermoplastic materials in the cable industry is not new. Gutta-percha and balata are natural thermoplastics which have long found important application for specific types of cable. In the past many natural thermoplastics have been incorporated into rubber compositions to give specific characteristics.

During the last ten years considerable progress has been made in the development of synthetic thermoplastic materials. Cable-makers have been extremely active during this period in adapting the basic materials developed to the peculiar requirements of cable. As a result certain cables of this type have been in service for about seven years. Naturally, economic considerations were allied with technical considerations in selecting the types of cable to be insulated and/or sheathed by such materials. Owing to the high cost of synthetic materials, these prototypes were in the main cables for which rubber was obviously an unsuitable material. With the outbreak of war, the number of types of cable in this category increased rapidly and development work was accelerated. Nevertheless, progress was unfortunately slow, and the consumption of synthetic thermoplastics by the cable industry was probably less than 5% of the rubber consumption in 1941.

The rubber crisis brought about a complete change in the situation. Cost was no longer the major consideration; substitution of rubber was the primary factor. It was evident that synthetic materials would have to be employed on an unprecedented scale. The United States and Canada embarked upon an ambitious programme of synthetic rubber production. It was obvious that some years must elapse before this programme could become effective and the users of rubber (including cable-makers) could become correspondingly skilled in the application of such materials. Increase in the production and usage of thermoplastic materials could be achieved much more rapidly. There were sound reasons to justify the belief that certain of these materials could be successfully used as substitutes for rubber—particularly by cable makers.

As a result, during 1942 and 1943 there has been a rapidly increasing output of essential cables insulated and/or sheathed with thermoplastic materials, so that several thousand tons of rubber have been saved. Probably 25% of the output of rubber cables has been changed over to thermoplastic materials.

It is natural that the advent of such substitute cables should have excited interest among cable users—queries such as those raised by the Chairman of this Section in his Inaugural Address‖ have been raised many times in the technical Press. These queries could best be met by a direct comparison between thermoplastic cables and rubber cables; this is, however, impracticable at present. Cables insulated and/or sheathed with synthetic rubber are already making their appearance. The cable designer of the future will have at his disposal an extended range of materials. None of these will be identical with rubber; each will have certain points of superiority and certain points of inferiority. The comparative costs cannot at present be estimated. To endeavour at present to forecast the position a few years hence would be unscientific.

This paper is therefore confined to a discussion of the characteristics of thermoplastic cables with particular reference to those insulated and sheathed with p.v.c. It is hoped that any future analysis of the wire and cable situation may be based on a true appreciation of the merit of thermoplastics in spite of the fact that they differ in many ways from natural and synthetic rubbers.

P.V.C. has been chosen as the main material for consideration in view of its very considerable usage in America and in Great Britain. A series of standard specifications has been designed round this material both in America[1] and in this country. It should be pointed out, however, that the American specifications refer to thermoplastic insulation and sheathing materials, whereas the addenda to B.S. 7, B.S. 883, and the various G.D.E. Specifications deal specifically with p.v.c. It has been considered reasonable, therefore, that the scope of this paper should be broad, and that reference should be made wherever necessary to thermoplastics other than p.v.c.

(2) THERMOPLASTIC MATERIALS

A thermoplastic material is one which when heated above a certain temperature becomes soft and will flow under pressure. When cooled it returns to its original condition. This cooling and heating cycle can be repeated indefinitely without chemical change in the material. P.V.C. and its co-polymers, polythene, etc., are typical thermoplastics.

Thermoplastic materials contrast with thermosetting materials: compounded rubber, phenol-formaldehyde resin, urea-formaldehyde resin, etc., when heated, change from the thermoplastic condition to a set infusible state in which they will no longer flow when heated. Raw rubber is essentially a thermo-

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‖ A. G. RAMSEY: Installations Section Chairman's Address, *Journal I.E.E.*, 1944, 91, Part I, p. 21.

plastic material, whereas compounded rubber, containing the necessary vulcanizing agents, is a typical thermosetting material. Neoprene is also a typical thermosetting material since it will vulcanize or set, merely by heating.

Some thermoplastics have a relatively sharp softening point, e.g. polythene at about 105° C, whereas others pass through a steadily varying change of state as the temperature is adjusted; the softening point can only be judged by arbitrary standards (see Fig. 1). P.V.C. in general belongs to the latter class, and

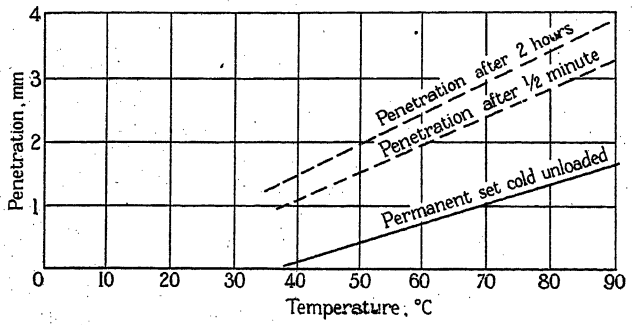


Fig. 1.—Flow properties of P.V.C. No. 1002 compound.
¼in diameter rod with ¼in hemisphere at foot.
Weight applied: 2 kg.

it will be found to yield under pressure over a wide temperature range, the degree of yield varying steadily at regular pressure as the temperature is adjusted.

In the former class the plastic range is bounded at the higher temperature by the decomposition point and at the lower by the relatively sharp setting point or softening point. In the latter class, however, the lower temperature is bounded by the brittleness point under the pressure applied.

Another outstanding difference between polythene and p.v.c. is worth mentioning here. Polythene is a translucent wax-like material having marked plastic characteristics *per se*. P.V.C. on the other hand is a white powder; its plastic properties are latent, and only become evident when plasticizers and other materials are added.

Materials such as p.v.c., which depend upon the type and content of plasticizer present for their thermoplastic properties, may have their plastic range extended considerably by the degree to which they are plasticized, though at the same time suffering decreased rigidity at air temperature.

Some quantitative representations of the growth of plasticity as the temperature is increased can be obtained by measuring the permanent set arising from deformation by a plastimeter or penetrometer. Fig. 1 illustrates this for a p.v.c. compound of the 1002 type. Permanent set is negligible until the material is subjected to temperatures in excess of 45° C. Cable experience suggests that the material will be satisfactory up to 55–60° C. Although the plastic properties of thermoplastics begin to be evident at the softening temperature, these properties are not sufficiently well developed to permit processing of the material. Much higher temperatures are necessary; e.g. with p.v.c. compounds, temperatures above 120° C are required.

When thermoplastic materials in general, and soft p.v.c. compounds in particular, are distorted at ordinary temperatures and within the elastic limit, they do not always "snap" back to the original shape as does vulcanized rubber. Furthermore, the time taken to recover the original shape is dependent among other things upon the degree of distortion and the type of compound. In other words, although these materials are elastic they are "dead" compared with rubber. This slow elastic recovery is, however, quite adequate for most cable applications.

Each thermoplastic material has its own peculiar elastic characteristics. Polyisobutylene is highly elastic; polystyrene at air temperature is practically inelastic. The elasticity of p.v.c. is a variable depending upon the type and content of plasticizer.

(3) POLYVINYL-CHLORIDE POLYMERS AND CO-POLYMERS

Many of the synthetic thermoplastic materials used in cable manufacture are polymers: chemically, the material consists of long-chain molecules containing repeating units. P.V.C. is such a material, and so is polythene. Implications of polymerization are indicated in Fig. 2. P.V.C. is a straight polymer, i.e. it is

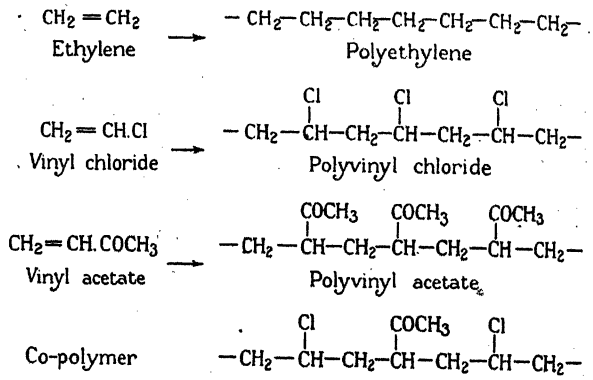


Fig. 2

built up solely of repeating units of vinyl chloride (which is derived from acetylene). However, polymers can be prepared which contain vinyl chloride and a minor proportion of a second ingredient in the straight chain. These materials are known as co-polymers. One type, Vinylite VYNW, which is vinyl chloride 95% and vinyl acetate 5%, is in many respects similar to p.v.c., and has been widely used for the same purposes. In effect, the discussion on p.v.c. can be taken to include this material. Recently a review of the vinyl-chloride/vinyl-acetate co-polymers has been made by Benedito.[2] He deals with grades of varying acetate content and varying molecular weight, and indicates the difference in characteristics obtained from such variation.

Fig. 3, taken from the Koroseal Handbook,[6] illustrates the pronounced effect on the tensile strength and hardness of a p.v.c. compound brought about by varying the molecular weight (represented by specific viscosities) of the polymer. Other chemical derivatives may be employed to make suitable co-polymers. An outstanding example is acrylic ester, which was employed with vinyl chloride to prepare the German material Mipolam. It must be clear that there is considerable scope for producing a variety of materials which can be known as p.v.c. It is essential, therefore, to bear in mind the source of the raw material, since alterations of technique in the polymerization process may affect the characteristics of the product.

In present circumstances there is no opportunity of selecting raw materials. Whichever type of p.v.c. is available must be utilized. The statements made in this paper are therefore limited to p.v.c. in its general meaning.

P.V.C. is a straight-chain polymer which shows no tendency to cross-linking. In other words, it is truly thermoplastic and does not set or vulcanize when heated. This applies equally to polythene, which is also a straight-chain thermoplastic material derived from ethylene. The molecule of polyethylene contains no groupings with any polar tendencies. Consequently it is relatively non-polar and exhibits correspondingly good electrical characteristics, e.g. low power factor, constant at all frequencies, coupled with low permittivity and high resistivity. Vinyl chloride, from which p.v.c. is derived, differs only from polyethylene

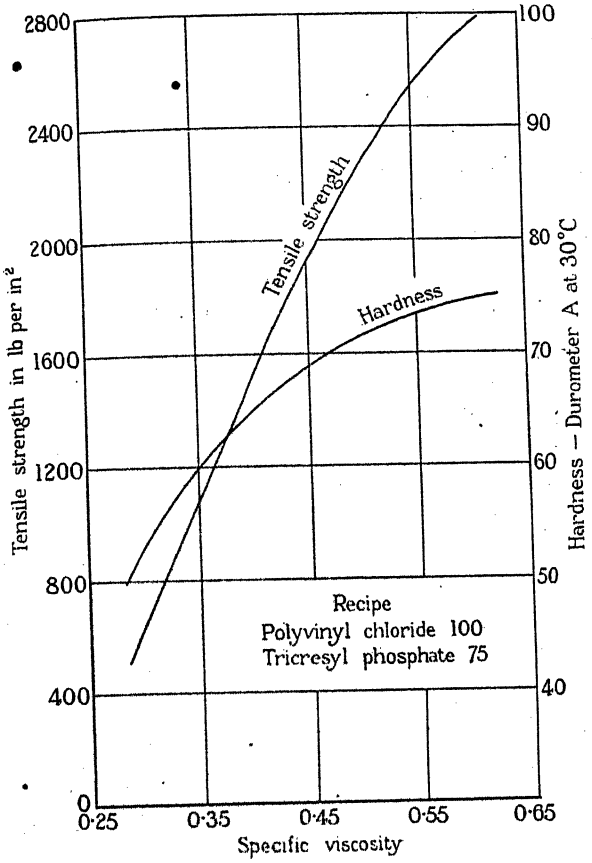


Fig. 3

in containing a chlorine atom instead of hydrogen (see Fig. 2). This introduces a polar material which adversely affects electrical properties; on the other hand it notably improves such characteristics as flame resistance.

As noted above, p.v.c. is not used alone. It is true that it can be moulded at temperatures above 120° C under a pressure of 500 lb/in². The moulding obtained is, however, hard, brittle, and somewhat dark in colour.

The pioneer in the evolution of polyvinyl compositions was Ostromislensky.[3] Following on his work, Semon[4] evolved the prototypes of present-day materials. About 1927, Semon found that the odourless, tasteless, chemically-inert, non-inflammable white powder, p.v.c., was insoluble at ordinary temperatures in practically every known liquid. On the other hand, he found that at high temperatures it was swelled and dissolved by tricresyl phosphate. On the basis of this work he developed a method for plasticizing the material, and polyvinyl compositions of the Koroseal type became commercially available.

(4) POLYVINYL-CHLORIDE COMPOUNDS

(4.1) General Discussion

There are many commercial proprietary materials available. Among the best-known types are Welvic and Chlorovene in this country; Koroseal, Vinylite, Flamenol, etc., in the United States; and Mipolam in Germany. A number of grades of material are available under each trade name.

In Great Britain, under war-emergency conditions, it has been considered necessary to establish a measure of standardization for the duration of the emergency. Specifications relating to characteristics have been evolved, notably G.D.E.S.18. Recently, standardized compounds have been adopted,[5] the composition of each compound being specified quantitatively. In this manner the limited supplies of polymers, plasticizers, etc., have been assigned in the most effective manner to specific types of cable materials.

The general make-up of the p.v.c. composition comprises:

Polymer
Plasticizer
Stabilizer
Lubricant
Pigment
Filler
Extender

The first four items are absolutely essential to the make-up of useful compounds; the others may be desirable for various purposes. The characteristics of the resulting compound will be greatly influenced by the proportions of these ingredients. It is desirable to consider them at greater length.

(4.2) Polymer

This component has been dealt with in some detail in Section 3, where an indication was given of the effect on the compound of the type of resin (polymer) employed.

(4.3) Plasticizers

No p.v.c. compound is suitable for cable manufacture unless it contains one or more plasticizers. The choice of plasticizer is of the greatest importance and profoundly influences the behaviour of the material. Most plasticizers are liquids of very high boiling-point and low volatility.

Many hundreds of plasticizers have been examined in p.v.c. compositions. The number which have been found suitable for large-scale application is, however, very small. The most important are tricresyl phosphate, dibutyl phthalate, and certain other phthalates. A few special plasticizers have latterly come into use in order to give improved properties at low temperatures.

The amount of plasticizer present profoundly affects the properties of the compound. Increase in plasticizer content causes a decrease in tensile strength and an increase in elongation. This feature is illustrated in Fig. 4. The hardness of the com-

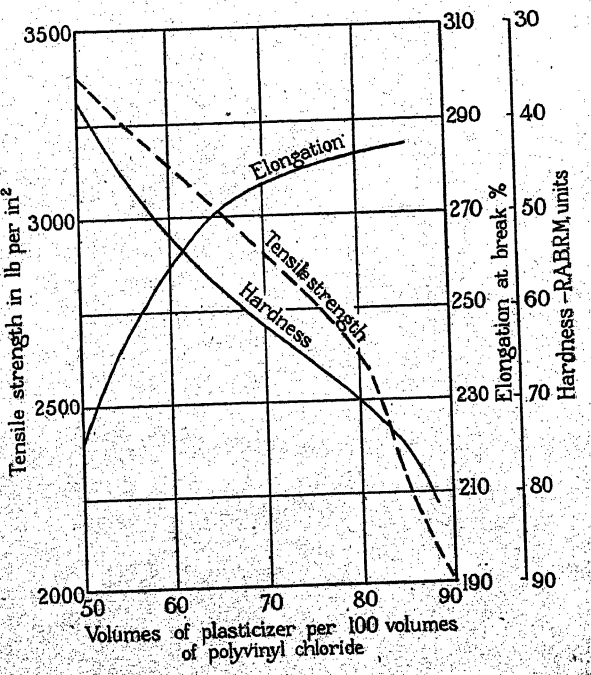


Fig. 4

position also decreases as the amount of plasticizer is increased. The relationship between tensile strength and hardness is, however, complex when the type of polymer or plasticizer is varied.

There are three features relating to plasticizers which are particularly important:—

(4.3.1) **Volatility.**

Although plasticizers have high boiling-point and relatively low volatility, with rise in temperature there is a certain degree of evaporation depending on the volatility. In some instances, e.g. tricresyl phosphate, the losses are minute. However, in others there may be appreciable loss of plasticizer. In this event the characteristics of the p.v.c. compounds change; correspondingly the characteristics of the cable may change, and it may indeed be rendered useless in extreme cases. A proper choice of plasticizer is therefore tantamount to selecting the potential maximum-service life of a cable for a definite set of conditions.

It has been found in this country that in general the most desirable set of properties is obtained in a p.v.c. compound when it contains a mixture of more than one plasticizer.

(4.3.2) **Leaching.**

Plasticizers may be soluble in water, oils or chemicals. Where this is the case, the cable must not come into contact with such substances; otherwise the plasticizer may be leached out, and once again the characteristics of the p.v.c. will be adversely affected.

(4.3.3) **Insulation Properties.**

For insulating purposes the plasticizer with the least harmful effect upon the electrical characteristics must be chosen and the quality of the plasticizer must be controlled by a strict specification.

(4.4) Stabilizers

P.V.C., subjected to high temperatures, particularly in contact with hot metal, tends to decompose with the evolution of hydrogen chloride. Normal processing involves the handling of p.v.c. compounds for short periods at high temperatures, e.g. around 150° C, in order to enable the compound to be applied to the cable. Decomposition products are most undesirable from every point of view. For example, they could adversely affect the electrical characteristics. It is therefore necessary to add stabilizing materials to prevent this decomposition, and it has been found that lead compounds are particularly effective. The principal materials employed for this purpose include white lead, litharge, lead chromate, etc. It is thought that stabilization is effected at least in part by the combination with the lead compound of any hydrogen chloride which may be formed. In the ordinary temperature range to which cables are subjected, p.v.c. compositions are completely stable.

(4.5) Lubricants

To assist in processing p.v.c. compounds during their application to the cable, it is usual to add a small proportion of lubricant. Typical materials employed for this purpose are ethyl palmitate, calcium stearate, etc.

(4.6) Pigments and Dyestuffs

Most p.v.c. compounds are noted for the brilliant colours they can exhibit if the necessary pigmentation materials are included. The standard colours adopted in this country are nine in number, namely red, black, yellow, green, blue, white, brown, orange and grey. In America, a few additional made-to-order colours are marketed, including pink and purple. The addition of pigments to the compound can affect both its electrical and its physical characteristics, so that great care must be exercised in making such additions.

In this country a very careful study has been made of the effect of colour pigments with a view to reducing differences between coloured compounds to a negligible degree.

The other physical effects of pigments can best be dealt with under the general heading of Fillers.

(4.7) Fillers

The main effect of inorganic fillers such as silica, mica, clay, carbon black, etc., is to increase the hardness in approximately a linear relationship in respect of quantity added. Resins, waxes, factices, etc., on the other hand, reduce hardness. The former class, with certain exceptions, however, reduce both tensile strength and percentage elongation. In general the use of fillers must be restricted to comparatively small amounts. Carbon black and clay in small amounts can increase the electrical resistivity, the latter in some cases raising the resistivity by 10 times at 70° C.[6]

The addition of a filler to a p.v.c. compound can very substantially reduce the abrasion resistance. Duggan[7] has published curves showing considerable increase of abrasion loss for comparatively small additions of filler.

(4.8) Extenders

In this country, a technique has grown up in the use of certain materials such as cereclor and aromatic extracts (from petroleum) as extenders. These materials if used with suitable plasticizers appear to do more than extend the compound—they confer certain special characteristics. It is perhaps preferable to consider such materials as extenders of the plasticizers. As mentioned with respect to resins, waxes and factices, they exert a softening effect, and they can add appreciably to the tensile strength, elongation, and flexure resistance; they are highly resistant to oils, solvents and water, and are very resistant to ageing.

(4.9) Standard Compounds

It will now be obvious that a wide range of characteristics can be achieved by skilled variation of the quantities and types of the various ingredients incorporated in a p.v.c. compound. It is misleading, therefore, to refer to p.v.c. as if it were a single material.

As already stated, standardized compounds have been set up in this country to cover the general run of p.v.c. cable manufacture under war-emergency conditions. These compounds have been carefully chosen and well balanced. It must not be assumed that they represent the full range of compounds which can be obtained from the known polymers, plasticizers, fillers, extenders, etc. Standardization in present conditions necessarily implies that unavoidable restrictions are applied to the performance of several types of cable in order to obtain certain characteristics in other types. When control is withdrawn and technical design is no longer subject to artificial limitations, the case for p.v.c. cables will undoubtedly be strengthened since one of the main points in favour of p.v.c. is the flexibility of design rendered possible by the range of known compounding materials. Natural expansion of the use of many thermoplastics in the cable industry in fields where their unique properties render them superior to rubber will then proceed unhampered by the present war-emergency restrictions.

(5) TESTING AND EVALUATION OF P.V.C. COMPOUNDS

(5.1) General

P.V.C. compounds can be designed to meet the specified cable requirements, but a great deal depends on the testing technique employed to evaluate the properties of the compounds. The cable requirements must be translated into material requirements which in turn must be interpreted in terms of standardized tests. In 1942, the setting up of standardized tests for the essential

Table 1

CHARACTERISTICS OF COMPOUNDS TO MEET G.D.E.S.18.

Compound	Usage	Cold flexibility		Tensile strength		Elongation at break		Water absorption: gain in weight (Note 2)		Leaching of plasticizer in water: loss in weight (Note 2)		Hardness R.A.B.R.M.* units: normal range	Cold impact: normal range (Note 3)	Thermal deformation: typical value (Note 4)	Permittivity: normal range	Resistivity: typical value	Electric strength: typical value
		Spec. value	Typical value	Spec. min.	Normal range	Spec min.	Normal range	Spec. max	Normal range	Spec. max.	Normal range						
		°C	°C	lb/in²	lb/in²	%	%	%	%	%	%		°C	%		ohms/cm cube	volts/mil
1001	Sheathing	— 30	— 35	1 000	1 500–2 600	150	250–400	6·75	2·0–4·0	0·9	0·06–0·10	65–85	— 25 to — 35	22	8·0–9·0	2×10^{10}	400
1002	Insulation	— 25	— 25	2 000	2 000–3 000	150	250–380	4·5	0·4–1·8	0·9	0·08–0·23	55–65	— 20 to — 30	16	6·0–7·0	3×10^{13}	500
1003	Insulation (audio frequency)	— 30	— 30	1 000	2 400–3 300	150	290–350	4·5	0·5–1·9	0·9	0·06–0·20	50–65	— 15 to — 25	15	4·5–6·0 (Note 5)	5×10^{12}	475
1004 (Note 1)	Sheathing (arctic)	— 40	— 55	1 000	1 400–1 800	150	290–430	6·75	1·1–1·8	0·9	0·10–0·40	85–115	Below — 50	22	—	—	—

NOTES—1. This compound has not yet been included in G.D.E.S.18.
2. Reduced to a percentage basis by using a specific gravity of 1·355.
3. Measured by a method generally adopted by the cable industry (not specified in G.D.E.S.18).
4. Measured at 70° C by the method described in Section 5.3. Duration of test—48 hours.
5. Compound No. 1003 is tested at 1 kc/s; the other compounds are tested at 50 c/s. Tests are taken at 20° C unless otherwise indicated.
* Research Association of British Rubber Manufacturers.

characteristics was attempted, and as a result G.D.E.S.18 was issued. It is not proposed to discuss in detail that specification, but rather to trace later developments in order to give a picture of the problems involved. At the same time the general behaviour of p.v.c. compounds from the viewpoint of their application to cables can be indicated.

Table 1 lists the major characteristics of the standardized compounds in terms of the testing technique of G.D.E.S.18.

In its original form G.D.E.S.18 depended largely on the production of cable samples formed by extruding a 50-mil wall of insulation round a 1/0·036 in conductor. In this form of sample the material has been processed in a manner identical with that of extruded cables and is therefore truly representative of cable insulation. There are, however, many sound objections to such samples, notably the important factor of quantitative accuracy, and they are therefore gradually being eliminated from the specification and replaced by moulded sheet. This has reacted in particular on the thermal deformation test and on the majority of the electrical tests.

The tests to which detailed consideration is given include flexibility, thermal deformation, ageing and the electrical tests.

(5.2) Flexibility

The simplest test for the flexibility of an insulated wire is to wind it round itself; no cracking or flaking should occur. Wires insulated with p.v.c. compound of the types in general use should pass this test with ease. However, such a test would not aid the cable maker in deciding how much plasticizer to incorporate in the compound. What he requires is a test which indicates at what temperature flexibility approaches zero. This enables him to adjust the compound so that the insulated wire or cable remains flexible at the lowest temperature the cable is likely to meet in service. It must be borne in mind that excess plasticizer reduces the tensile strength and hardness obtainable, usually degrades the electrical characteristics, and increases the thermal deformation exhibited at the required maximum working temperature of the cable. Thus, while it is practicable to make compounds which are flexible down to, say, — 60° C, more normal practice is to reduce the plasticizer content so that flexibility ceases at about — 30° C or even higher temperatures (see Table 1).

As will be seen from a study of G.D.E.S.18, tests are made on strips of the compound. Considerable development has taken place in the apparatus employed, in order to eliminate as far as possible the human factor and to obtain repeatable results of high accuracy. Fig. 5 illustrates the most modern type of apparatus for carrying out this test in accordance with G.D.E.S.18. It is now possible to obtain such accuracy in the

Fig. 5.—Cold-bend test machine.

test that changes in the plasticizer content can be determined with fair accuracy. Thus, for example, it is possible to check the effect of water immersion, not only by the gravimetric method given in the original G.D.E.S.18, but also by a cold flexibility test, which is even more practical in its bearing. A pronounced change in the temperature at which flexibility vanishes would indicate that the plasticizer had leached from the compound during the period of water immersion.

Similar effects can be obtained by checking the temperature corresponding to zero flexibility before and after ageing.

Cold bend or flexibility should not be confused with cold impact or shatter resistance. In general, the latter approaches zero at a somewhat higher temperature than flexibility. There is reason to believe that the impact resistance of p.v.c. is much greater than that of rubber compound over the range from 0–60° C. Impact resistance is related to the type and quantity of plasticizer in the compound. This is another characteristic which requires much more study—including standardization of the method of test. Work in this direction is being vigorously pursued.

(5.3) Thermal Deformation

It must be admitted that the study of thermoplastic behaviour of p.v.c. at temperatures of the order of 70–85° C is still incomplete. Certain classes of p.v.c. compounds are associated with a slow but persistent yield under stress at elevated temperatures, and it is difficult to forecast the limit of such yield under a short-period test.

In the manufacture of cables it is necessary to ensure that the conductor will not penetrate the insulation to such an extent that electrical breakdown may result, either under its own weight or under stresses set up by the installation of the cable. The specifications for certain service cables include tests in which a short sample is suspended over a suitable metal mandrel and loaded with weights at each end. The loading weights on a 30–40 mil wall may be as high as 2×60 lb, or even 2×125 lb (braided cable). The conductor must not cut through the insulation and "short-circuit" to the mandrel after periods of 24 or 48 hours.

It originally seemed sound to make the thermal deformation test of G.D.E.S.18 on the 1/·036 in insulated conductor mentioned above, but with the modification that the depth of the penetration in a given time under a given weight-loading was measured. This method had several disadvantages and has now been replaced by an ingenious alternative illustrated in Fig. 6.

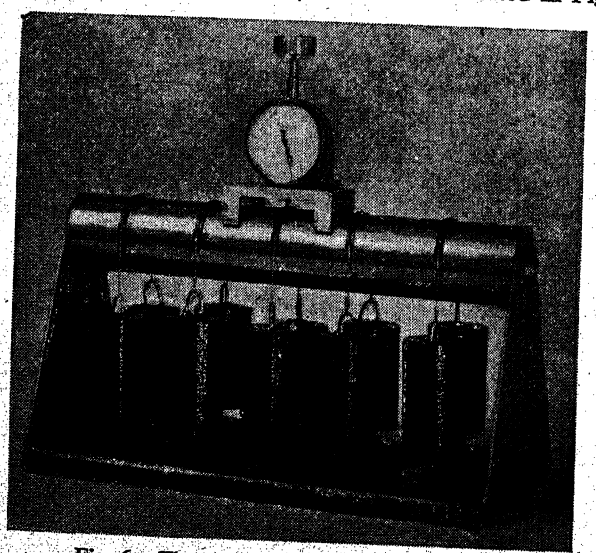


Fig. 6.—Thermal-deformation test apparatus.

Strips of the compound are hung round a special mandrel and their thicknesses measured. 1/·036 in wires, loaded with the desired weights, are hung one over each strip and are measured *in situ* so that the total thickness of strip plus wire is accurately determined in each case. As penetration proceeds, the reduction of this total thickness can be determined by the micrometer and, if desired, a curve of deformation against time can be plotted (Fig. 7). Furthermore, on several of the loaded wires the

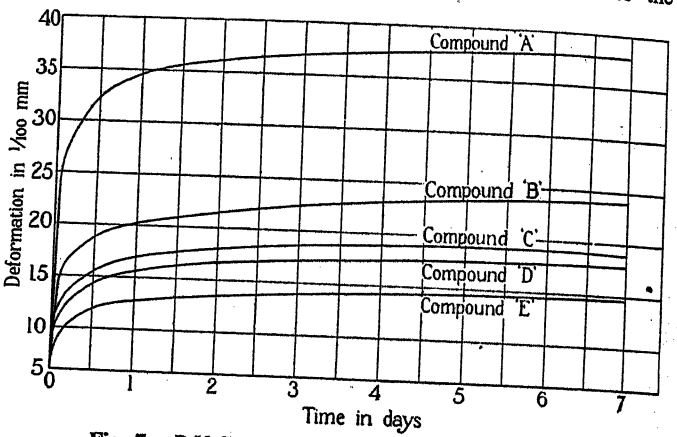


Fig. 7.—P.V.C. thermal deformation test (at 70° C).

recovery of the compound can be measured and recorded on a time base, this method giving considerably more information on the behaviour of the compound. It will be noted that the curves of Fig. 7 tend to become asymptotic to a certain deformation value: this implies that in general, at least under low stresses, the material ceases to flow after a short time.

(5.4) Ageing

Oxidation is absent from the ageing characteristics of a p.v.c. compound; the oxygen-bomb method of test favoured by certain rubber technologists is therefore useless. The point which requires checking is the loss of plasticizer.

Since, however, as previously mentioned, the design of the compound is largely built round the plasticizer, it is reasonable to include in specifications such as G.D.E.S.18 an accelerated ageing test to check the change in mechanical properties produced thereby. It is obvious that the test should comprise the determination of one or more of these properties before and after application of heat and air currents to the sample. Again, however, it is found that the selection of the exact conditions of test to give an accurate representation of the ageing effect is most difficult. Originally, tensile strength and elongation were chosen as the mechanical properties to be examined. Fig. 4 indicates why tensile strength should increase with loss of plasticizer; similarly elongation decreases. But it was found that these properties are not ideal for establishing accurate differences before and after ageing. Change of cold flexibility (zero) temperature has also been considered (see Section 5.2). Hardness (Fig. 4) may also be a sufficiently sensitive test. The correct combination of temperature and air flow is also difficult to settle.

Obviously the temperature chosen for the ageing test should be in excess of the maximum rated working temperature of the p.v.c. compound. The correct air-flow is, however, one which must be settled arbitrarily, since it is difficult if not impossible to assess the expected air-flow in service. There is also the difficulty that rapid air-flow tends to cool the sample unless heated air is used, and this complicates the apparatus.

It must also be remembered that tests on strips are not directly related to tests on cable where the volatilization at the inner surface may approximate to zero. Also, the p.v.c. in the cable

ay be protected to some extent from volatilizing effects by a aid or tape which is impregnated or lacquered. In the United tates the view is apparently held that lacquered braiding has iis effect.

All in all, there is not much hope at present of correlating an ccelerated ageing test with the average ageing characteristic of cable in any particular type of service. Auxiliary data are eing collected by the examination of cables which have had a ervice life of some years, but, since p.v.c. cables have in general nly had a few years' life, some time must elapse before a comrehensive statement can be made on the subject. Meanwhile, ıccelerated ageing tests are employed both on compounds and ɔn cables to ensure that no undue deterioration can occur.

(5.5) Abrasion

Experience in the field with p.v.c. sheathed cables seems to indicate that the abrasion resistance of the material is of a somewhat higher order than average tough-rubber sheath. This is borne out to some extent by laboratory tests, but here again there is some difficulty in setting up a standard test which would permit the accurate estimation of the quantitative effect of various plasticizers, extenders, fillers, etc. So far, no test of this type has been included in G.D.E.S.18, although certain cable specifications include tests on the finished cable. Duggan[7] has carried out work which seems to confirm the view that the abrasion loss of p.v.c. tends in general to be considerably less than that of a normal rubber.

(5.6) Electrical Tests and Characteristics

With the exception of electric strength, the electrical characteristics of p.v.c. are so dependent upon the polymer, plasticizer, extender, filler, etc., employed that a careful check must be made of the compound to determine whether the specified requirements have been met. Table 1 indicates that the resistivity of compounds which have been plasticized to give − 30° C cold flexibility ranges from 1×10^{10} to 1×10^{12} ohms/cm cube at 20° C. If less plasticizer is employed (cold flexibility − 25° C), values of 1×10^{12} to 1×10^{14} may be exhibited. Further raising of the cold-flexibility temperature coupled with the use of the highest electrical grades of polymer, plasticizer, etc., may enable the resistivity to be raised somewhat above 1×10^{15} at 20° C. This comparatively low maximum value is coupled with a steep resistivity/temperature characteristic which reduces the resistivity to about 1/100th of its value for a rise in temperature of 50° C. It will therefore be realized that p.v.c.-insulated cables are not particularly interesting from the insulation-resistance point of view. Fortunately this characteristic is seldom of real practical value in service. For thermoplastic cables which in service require high insulation resistance a non-polar material such as polythene must be employed.

Similarly, the dielectric loss of the material is high and extremely variable with temperature and frequency (Fig. 8). By careful selection of plasticizer and other ingredients, compounds may be produced having reasonable dielectric power factors (e.g. 0·05–0·06). In general, however, such selection imposes serious limitations on the mechanical properties of the compound.

The conclusion must be reached that, except during a war

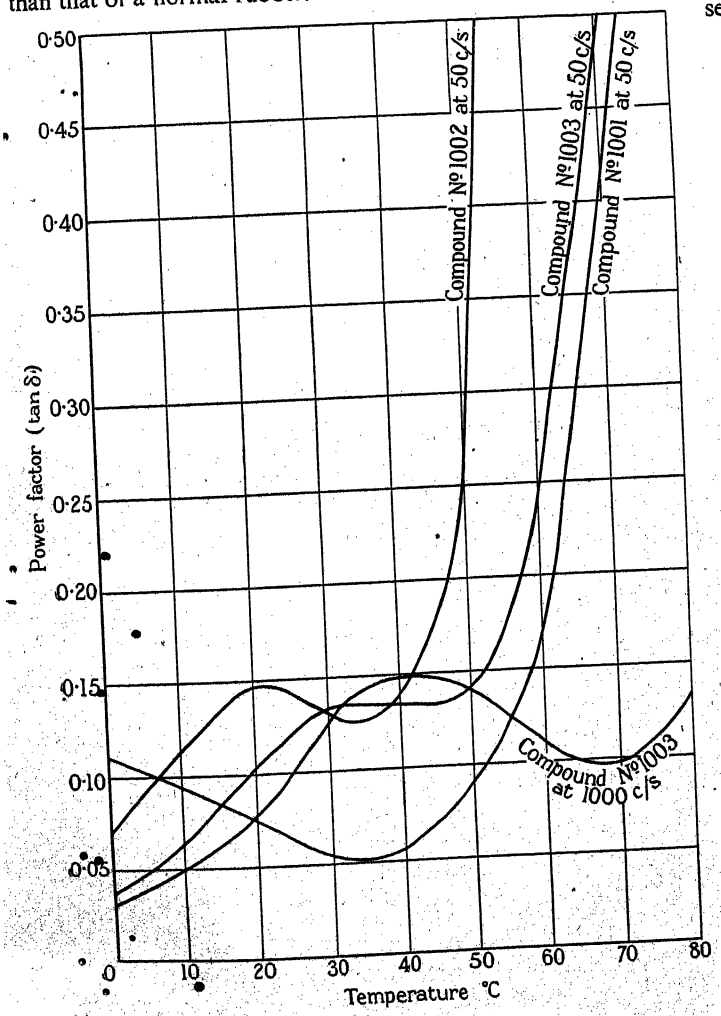


Fig. 8

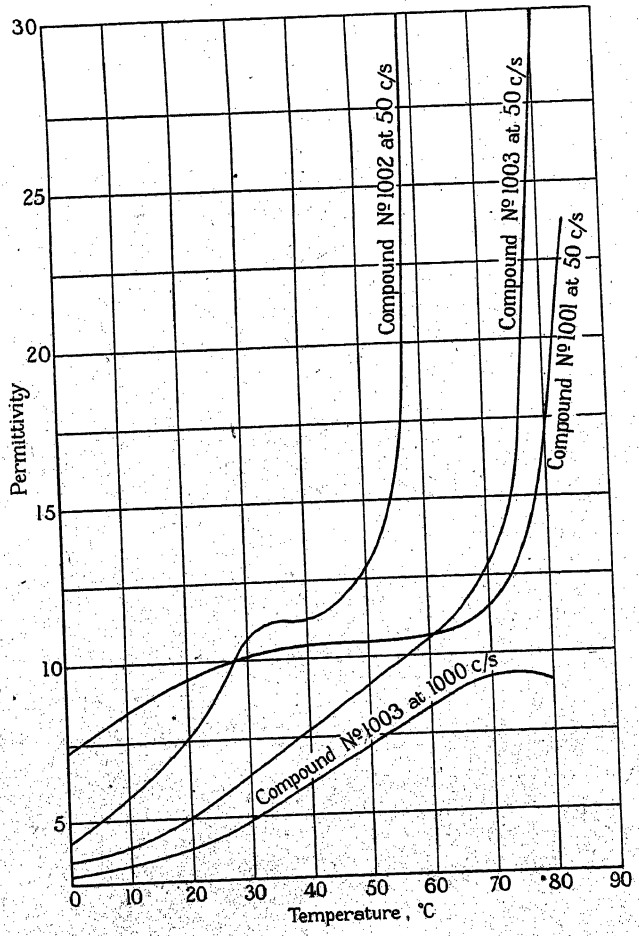


Fig. 9

emergency, p.v.c. is unlikely to be used as an insulant at frequencies greatly in excess of 2 kc/s.

Similar remarks apply to the permittivity which for an insulating grade at 20° C works out in general at 6 to 8. Special compounding can achieve values of 4·5 to 6 with the limitations mentioned above. Fig. 9 indicates that there is also a pronounced temperature coefficient for permittivity.

(6) MANUFACTURE OF P.V.C. CABLES

P.V.C. can be applied to the insulation of cables in at least three ways, namely taping, longitudinal-strip application, and extrusion. The first method is not used to any marked extent in this country, although it is used with success for certain types of cable abroad.

Longitudinal-strip application is a leading method in this country for applying natural and synthetic rubber compound. The process depends on self-adhesion of materials, in which property p.v.c. is lacking. This method, therefore, has presented certain difficulties and has involved cable makers in considerable development work. Success has been attained with braided p.v.c. cables, and there is considerable hope that success will soon be obtained with taped cores.

In preparing the p.v.c. strips for longitudinal application, some strains are set up in the material. These must be released by heat treatment (which also welds and consolidates the multilayer structure) under mechanical pressure in order to avoid splitting, etc., the pressure being most easily applied by braiding prior to heat treatment. It will be noted that the necessity for heat treatment to a great extent cancels the advantage claimed for a thermoplastic insulation in that it does not require vulcanization.

Extrusion is the normal method of applying insulation and the sole method of sheathing cables. P.V.C. is one of the easiest thermoplastic materials to extrude, and very fine results can be obtained in respect of concentricity, thin walls, etc.

It may be of interest to include a brief account of the stages of processing, leading up to extrusion of the insulation or sheath.

Compounding can be effected in dough mixers, open mills or Banbury mixers. In this respect it follows rubber practice closely.

Normally, p.v.c. resin will reach the factory in the form of a powder. Supplies of plasticizers in liquid form, together with other ingredients which are either powders, liquids, or pastes, will also be available. The appropriate proportions of the different substances required to provide the correct compound are weighed out and are usually thrown into a simple type of mixing machine. This provides a mechanical mixture, which may be a paste or a damp powder.

The mixture is then passed to a mixing machine in which the polymer is gelled by the plasticizers in a process which combines heat and mechanical working. It is here that the chemical stability of the mixture first becomes an important factor. In order to achieve satisfactory mixing of certain classes of compounds, comparatively high temperatures are desirable, e.g. 130° C. It is necessary to ensure that at these temperatures there will be neither decomposition of the p.v.c. molecule, nor any appreciable loss of the plasticizers or extenders.

After the material has gelled or plasticized in this machine, it is usually rolled into strip form for storage. In certain cases the soft dough may be transferred direct to the extrusion machine.

When strip is employed, it is usually first heated in a suitable oven at a temperature preferably not in excess of 80–90° C, and is then fed to the throat of the extruder. It is desirable that the temperature, both of the strip and of the extruder, should be maintained uniform in order to ensure uniformity in size and shape of the extruded composition.

Extruders are of various types, mostly similar to the well-known rubber type, though with certain modifications. The commonest difference is that an electrically-heated extension-head should be provided, which ensures an even flow of material through the die or orifice of the machine. Unlike rubber, which is often extruded without a positive haul-off and take-up mechanism, p.v.c. extrusion is nearly always accompanied by such a mechanism, and the size and uniformity of the extruded wire is usually controlled by varying the rate at which the wire is hauled through the machine. The usual take-up mechanism removes the cable or wire from the capstan and winds it on to the appropriate drum.

Temperatures at which extrusion is to be carried out will vary both with the type of machine and with the quality of the compound being extruded. Usually the die temperature is higher than 150° C; temperatures lower than this are liable to provide extruded cores or sheathing with excessive strain, which may give trouble in service.

Attention must be given to the design of the extrusion machine, particularly to the head and die. The main point is to avoid pockets which may cause prolonged local heating of any idle p.v.c. compound which may become lodged. This results in the deterioration and embrittlement of the latter due to loss of plasticizer or to thermal decomposition. When these cohered particles emerge they spoil the extrusion. Water cooling is customary, though not essential.

The speed of extrusion will clearly depend on a number of factors, such as the type of machine employed, the size of the cable being run, and the type of compound.

With the correct compounds and the appropriate temperature, it is possible to extrude p.v.c. into strips of insulated wires separated from each other merely by small fins. It is also possible, for example, to extrude spider sections (giving an air-spaced insulation) in a single operation. In fact, the intricacies of sections which may be extruded depend only on the ingenuity of the die designer and the ability of the machine operative. P.V.C. has unlimited possibilities in this respect.

Brief mention may be made of the methods employed for the manufacture of p.v.c. tubings. These are similar in most respects to those described for p.v.c. cable manufacture. It is usually desirable, however, in extruding p.v.c. tubes, to provide a small air pressure to the centre of the tube to prevent it from collapsing, the tube being carried away from the extrusion machine by means of a light conveyor system. This obviates the necessity for pulling or hauling the material from the die by the usual haul-off gear, which, though satisfactory for the centre wire of a cable, would be impracticable for a tube with uniform wall thickness and diameter.

No mention has been made of the use of strainer plates or gauzes in the head of the extrusion machine. Since p.v.c. compound is made from powders, liquids, etc., there is always some risk of undispersed particles of powder forming an agglomerate, which could cause faults in thin-walled insulation. It is desirable, therefore, though not essential, that extrusion machines should be fitted with appropriate strainers.

(7) CHARACTERISTICS OF CABLES

The outstanding qualities of p.v.c. are its resistance to sunlight, oxidation, fire, and a large variety of chemicals including oils—qualities in which rubber is somewhat deficient. These qualities, coupled with excellent resistance to abrasion and (within certain temperature limits) to impact, naturally draw the attention of cable makers to its potentialities as a sheathing material. The earliest applications of the material in the cable field were in this direction, particularly for aircraft and ships, and probably these applications account for the greatest consumption of p.v.c. compound at the present time.

The material, however, possesses very considerable resistance to electrical breakdown, with one notable exception to be discussed later. Since this is the primary characteristic of a cable insulant for power purposes, consideration was given to the use of the material as an insulant, particularly for thin-walled cables in which it was uneconomic to apply separate insulation and jacket, e.g. thin-walled flexibles for machine wiring, switchboards, etc., where the special qualities mentioned above, coupled with bright, easily distinguished colours, are assets of considerable value.

Whereas in the United States a specification[1] for ordinary building wire was introduced some time ago, in this country the decision to use p.v.c. as a principal substitute for rubber was not taken until early in 1942. The preliminary work leading to the modification of B.S. Specifications, etc., was then put in hand.

It is important, however, at this stage to note two very important points of divergence between the development of p.v.c. cables in America and Great Britain during 1942–3. For reasons which must be obvious but which cannot be discussed here, the selection of materials, e.g. polymers and plasticizers, is considerably restricted in Great Britain. Also the major consumption of p.v.c. compounds is for Service cables. Naturally this consideration imposes severe restrictions. All compounds developed and utilized for cable-making have therefore been designed with Service requirements as the target. Reference to G.D.E.S.18 indicates that low-temperature flexibility is a primary requirement, setting a standard of plasticizer content which predetermines many other characteristics. The American specification[1] contents itself with compounds meeting less restrictive and more general requirements.

The electrical and mechanical characteristics at maximum operating temperatures are somewhat different in the two countries, the electrical resistivity and the resistance to thermal deformation being somewhat higher in the United States. There is, however, reasonable agreement on the maximum safe working temperature for unbraided insulation, namely 60° C (U.S.A.) and 57°-C (Great Britain). For insulation working above 60° C in the U.S.A. it is deemed desirable to add braiding. The reasons are not the same as those associated with the use of braid in rubber cables; they are (*a*) to minimize volatilization of plasticizer, and (*b*) to improve resistance to thermal deformation. With such precautions and using normal American mixes it is considered practicable to work cables at 75° C (U.S.A.).

As noted above, the electrical characteristics of p.v.c. (apart from electric strength) are not particularly good, and if a high-quality standard is required in respect of insulation resistance, permittivity or dielectric loss, then p.v.c. is a questionable choice. The electric strength of p.v.c. is, however, sufficient for all purposes except high-frequency working. Owing to the high losses and considerable temperature coefficient, thermal breakdown may be expected if appreciable voltages at frequencies of the order of megacycles are employed.

Mechanically, the insulation and sheathing produced from p.v.c. compound is somewhat difficult to evaluate scientifically. In this country it is largely used to replace rubber. The elastic properties of p.v.c. have been discussed in Section 2. It cannot of course replace resilient tough-rubber sheath owing to its lack of resilience. It can, however, replace ordinary tough-rubber sheath, often with the introduction of improved characteristics. As an insulation it is noteworthy that it has seldom, if ever, replaced rubber when the service conditions of the cable have demanded that rubber compound not inferior to G.D.E.S.16, Amendment 3, must be employed—this despite its very considerable tensile strength. As against rubber compounds to G.D.E.S.16, Amendment 4, p.v.c. exhibits very good mechanical properties and produces cables which compare very favourably with their present-day rubber equivalents.

It must again be stressed that these comparisons are artificial. Both materials suffer from restrictions and control which are essential at present, but which do not permit of their best technical performance. The position under free technical and economic competition might be quite different. The present emergency substitutions of p.v.c. for rubber are, however, assisting in the compilation of essential data regarding performance in service which otherwise would emerge somewhat slowly. The experience gained over the next few years from the performance in service of such cables will go far to evaluate the mass of laboratory data in terms of practical performance. This will pave the way for the scientific application of thermoplastic cables in the post-war era for those conditions of service in which it may prove desirable and economic to employ them. To raise questions at present regarding the expected increase in life for a thermoplastic cable in comparison with a rubber cable is not entirely reasonable and can only lead to answers founded largely on laboratory data which are still inconclusive and incomplete.

On the other hand, the progress made in producing satisfactory thermoplastic cables is such as to assure cable maker and user alike that a valuable addition to the list of cable-making materials has arrived and has come to stay.

(8) USES AND INSTALLATION OF CABLES

(8.1) Uses

By far the greatest consumption of p.v.c. for cables at home and abroad is for Service purposes, in particular for aircraft and ships. We are not here primarily concerned with such applications, but rather with uses allied with B.S. Specifications, e.g. B.S. 7 and B.S. 883. It must be noted, however, that the close relationship between Addendum 3 of B.S. 7 and G.D.E.S.1, etc., is such that the Service requirements, e.g. cold flexibility, dominate the manufacturing situation and result in G.D.E.S.18 being applicable to both sets of specifications. For the time being at least, this universal adoption of G.D.E.S.18 is necessary. This applies also to B.S. 883 and to any other "civilian" cables which may be designed and manufactured.

Essential civilian uses lie mainly in the direction of installations in buildings and ships, machine and switchboard wiring, light-current wiring (including telephone cords). A recent addition to the range of p.v.c. cables is the insulated wire for miners' cap-lamps. A p.v.c. type of cleat wire is under consideration.

In drawing up specifications, it is usual to rank rubber and p.v.c. as equivalent materials, and to design the p.v.c. cables to the same dimensions as their rubber counterparts. There are one or two points of difference which merit comment. For the time being the maximum conductor size of p.v.c. cables is limited to 0·06 in^2. This limit will undoubtedly be raised as soon as the compound can be "hardened" by modifying the cold flexibility requirement. It may be raised before then by the development of new types of compound with a wider temperature range. It is, of course, not certain that present compounds are unsuitable for sizes of conductor of, say, 0·1 in^2, but further field experience is required and the methods of installation may need study.

For B.S. 7 cables it is considered (and approved by I.E.E. Wiring Regulations) that the overall braiding may be omitted, even for cables drawn into conduits when the conduits are modern and well constructed. It should be remembered that, for the present, braiding is essential in certain cases to permit the cable maker to bring his longitudinal-strip insulating machines into operation. It should be noted that American

practice omits braiding for cables working below 60° C (max), although recommending it for cables and wires used at higher temperatures. A considerable quantity of p.v.c.-insulated wire (both braided and unbraided) is already in service in this country. Discussion on this paper may produce some interesting comments from the point of view of the user.

P.V.C.-insulated wires have largely evolved from thermoplastic sleevings. Since these had to be extruded, it appeared reasonable to include the conductor in the process and produce "connecting wire." The p.v.c. insulation appears to give excellent performance. Such wires should, however, be used with discretion at frequencies of the order of megacycles. Some troubles with soldering have been experienced. The outstanding flexibility and resistance to flexing failure of the p.v.c. insulation are an attraction for items such as telephone cords.

Turning to ships' cables, the issue of the supplement to Amendment 3 to B.S. 883—1940 has been backed up by Notice No. 1805 from Lloyd's Register of Shipping, which at the same time gives an excellent résumé of the merits of p.v.c. and also lays down tentative amendments to the Rules for Electrical Equipment. These amendments limit the use of p.v.c. cables to 250 volts and to conditions where the ambient temperature is not greater than 45° C, and exclude such cables from open-deck situations exposed to the direct heat of the sun and from situations where the cable is attached to metal similarly exposed. These restrictions appear to be sound—at least until further experience is built up on the basis of service performance and until present-day restrictions on types of compound are removed.

It is to be anticipated that rapid progress will be made in both these directions, and that the use of p.v.c. cables on shipboard will cumulatively increase. A large amount of the p.v.c. compound used in America finds its way into ships' cables, and the maximum temperature ratings of certain types is of the order of 90–100° C. Special compounds and constructions, however, are used; one example is the employment of p.v.c. in place of lead sheaths for cables insulated with varnished cambric and/or asbestos. This appears to be attractive where high flexibility is a requirement and where weight saving is desirable. But it must be remembered that, although p.v.c. sheathing is resistant to moisture, like almost every other non-metallic membrane, it passes water vapour from the atmosphere to dehydrated fibrous material within it. The diffusion constant of normal p.v.c. is from $3{\cdot}8 \times 10^{-8}$ to $11{\cdot}4 \times 10^{-8}$ g/hr/cm/mm Hg, depending upon the type of compound. This value is of the same order as for rubber and is much worse than that for some other thermoplastics (e.g. polythene, $0{\cdot}3 \times 10^{-8}$). Nevertheless, it is to be expected that in due course some interesting developments in this particular field will evolve.

It should be noted that some p.v.c.-insulated and sheathed cables have been successfully operated when installed direct underground.

Apart from cables of conductor size greater than $0{\cdot}06$ in^2, several other development aspects are being investigated vigorously with a view to extending the scope of p.v.c. cables. These include flexible cords attached to high-power lamps, automobile cables, etc., where the temperature is high. Field trials have been instituted and a considerable amount of data have already been collected. It may be expected that any weaknesses exposed by such field tests can be corrected by adjustment of the compound employed—when this becomes practicable. A further point being checked by practical trial is the relative merit of multicore cables "filled" with fibrous materials as against cables "filled solid" with p.v.c. The latter type appear to be less flexible than their well-known rubber counterparts, but the loss of flexibility may be more than compensated by the gain in other mechanical properties.

(8.2) Installation

It has been said that to utilize thermoplastic cables successfully it is necessary to become "plastic minded," in contrast with the "rubber mindedness" now exhibited by makers and users. Installation is a very strong case in point. Users of p.v.c. and other thermoplastic cables must be prepared to revise many of the traditional installation methods employed for rubber cables. It is in installation that the greatest divergence will be observed between thermoplastic and rubber behaviours. An outstanding example is the use of unbraided cable in well-built conduits. It should be noted that such cables can be greased with petroleum jelly or similar lubricants to aid installation.

Repairs and jointing also present a somewhat different problem. Veit[8] has recently published an article devoted to this subject, and his principal point may well be re-emphasized, namely that heat alone will not weld thermoplastic joints; heat and pressure applied simultaneously are required. Given such an application, the repair and jointing of thermoplastics become simpler and neater than the corresponding rubber processes. One modern method of achieving this combination may be with the use of high-frequency heating—which is now finding applications in many directions. A general review of this technique was given recently in *British Plastics*,[9] and this review included a reference to one method particularly applicable to p.v.c and to p.v.c. cables.[10]

It may be of interest to describe two alternative methods of jointing on which proofed taped is employed to control the p.v.c. during the heating process.

Method 1

After jointing the conductor, p.v.c. paste, made by dissolving p.v.c. in cyclohexanone, is smeared along the conductor, and a portion of insulation, of the same length as the exposed conductor, is removed from the end of a similar cable, in the form of a split sleeve. The split sleeve is placed over the conductor and the paste is pressed into the split on the sleeve and at the ends where the sleeve is butting with the insulation proper. The whole is then tightly taped with three proofed tapes, proof-side down, and the repair is heated by means of a small gas flame or other suitable lamp until the outer tape changes to a creamy brown. The tapes are then removed.

Note.—In repairing a p.v.c. sheath to a multicore cable in which the core insulation is p.v.c., special care should be taken not to use too much heat when bonding the sheath.

Method 2

After jointing the conductors, the p.v.c. at each end of the joint is tapered down to the strand for a length of approximately twice the diameter of the cable. The whole of the exposed conductor should then be cleaned with a suitable solvent, such as benzene or petrol, to remove all grease or foreign matter. The insulant, in the form of a split tube of p.v.c. or a fine tape lapped on, is applied to the joint. Where the sheath is reasonably free to move on the conductor or core, it may be drawn back before jointing the conductors, and after making the joint the p.v.c. may be pulled back into position over the joint and over the other end of the p.v.c. insulant. In this case the conductor must be shortened. The joint is then consolidated as follows: A wrapping of metal foil (or two or three wrappings of proofed tape, proof-side down) is applied to the joint and extending a few inches beyond the repair. The whole joint is then heated carefully and evenly by means of a gas flame or a gentle flame from a blowlamp until consolidation occurs. When using the proofed tapes, this will be achieved when the outer tape changes to a creamy brown. Alternatively, the taped cable may be immersed in a wax bath for sufficient time at approximately

250° F to ensure consolidation. After cooling, the proofed tapes may be removed.

Other methods, employing special accessories, e.g. moulds, have also been developed.

The soldering of thermoplastic cables is a matter which requires study by users. There are complaints from time to time that the insulation of p.v.c. cables shrinks unduly when a soldering iron is brought into contact with the conductor. Soldering is undoubtedly a troublesome operation under present conditions. It is necessary, for example, to cater for some of the troubles by including tinned conductors for p.v.c. cables when the diameter of the individual wires constituting the conductor is less than 0·029 in—despite the fact that p.v.c., unlike rubber, does not require tinned conductors for chemical reaction reasons. An undue amount of heat and/or an undue prolongation of application of heat should undoubtedly be avoided in soldering thermoplastic cables. All possible precautions to aid the removal of heat from the insulation should be employed. Without such precautions, for example, polythene becomes a viscous liquid and will leave a gap between the soldered connection and the adjacent insulation. Excessive heat leads to the shrinkage phenomenon experienced with p.v.c. Investigation of the phenomenon has been made and is continuing. Braiding definitely tends to minimize the effect, but the effect on unbraided cables is erratic in that it only in some cases occurs. This is undoubtedly due to the fact that the shrinkage is caused by the sudden and uncontrolled release of strain set up in the p.v.c. during its earlier processing. It should be stressed, however, that very many p.v.c. cables are soldered daily without this phenomenon appearing.

Another aspect of the study of thermoplastic cables must be considered, namely the application of pressure in cleats, clips and water-tight glands. Deformation of p.v.c. compounds considered suitable for normal cable work can only become serious when there is a combination of heat and pressure and in particular when the pressure "follows up" the deformation. At ordinary temperatures and with pressures which fall off as the material tends to yield, deformation cannot be serious. Cold flow in its correct sense should not be observed in a well-designed p.v.c. cable.

It must be appreciated, however, that the design of a gland for a thermoplastic cable differs considerably from that of a gland for a vulcanized-rubber cable. Users of such glands would be well advised to seek expert advice on this subject.

(9) THERMOPLASTICS OTHER THAN P.V.C.

(9.1) General

It is unfortunate that space and other considerations prevent the presentation of a complete survey of the thermoplastic cable field, the more so since no such complete survey appears to have been published. In 1939, Schatzel[11] gave a broad picture of the position in the United States. During 1943, Veit[12] has written an article on the subject, but like the present paper it naturally emphasized the p.v.c. aspect. Similarly Chapman[13] devoted most of his recent paper to p.v.c. Barry, Tunstall, Pollett and Jesson[14] have written a series of articles on synthetics as applied to cables which covers a somewhat wider field than the other writers mentioned.

Pending the presentation at a suitable date by some competent author of a broad review of thermoplastic materials (other than p.v.c.) applied to cable-making, it would appear to be useful to include here a brief comment on some of the other materials which may in the near future be influencing the trend of ordinary wire and cable design (see Table 2).

Table 2

ELECTRICAL CHARACTERISTICS OF THERMOPLASTICS (OTHER THAN P.V.C.) EMPLOYED IN DIFFERENT FORMS OF CABLE MANUFACTURE

	Polystyrene	Polythene	Polyisobutylene	Ethyl cellulose	Polyvinyl formal	Nylon
Electric strength, volts/mil	900	1 000	900	1 200	750	400
Resistivity, ohms/cm cube	10^{17}	10^{17}	10^{16}	10^{14}	10^{14}	10^{13}
Permittivity:						
at 50 c/s	2·5	2·3	2·3	3·2	3·7	3·2
at 1 000 c/s	2·5	2·3	2·3	3·1	—	3·3
Power factor:						
at 50 c/s	0·0002	0·0001	0·0004	0·013	0·0007	0·018
at 1 000 c/s	0·0002	0·0001	—	—	—	0·025

Note.—The above values apply to the pure unplasticized material; where plasticizers or other compounding ingredients are added the characteristics will be proportionately affected.

(9.2) Polythene

This material has been mentioned from time to time in this paper since, while contrasting definitely with p.v.c. in many of its characteristics, it is in some ways a complementary material. A combination of polythene insulation with p.v.c. sheathing may well prove to be the ideal thermoplastic cable combination for most purposes. High insulation-resistance, low permittivity and dielectric loss, etc., can thus be obtained in conjunction with all the merits of p.v.c. expounded above. It is understood that the electrical properties of polythene will be dealt with in a paper to be read before this Institution in the near future, so that detailed discussion need not now be entered upon. It is sufficient to comment that the material is already well-developed as a cable insulant and is giving excellent service performance.

(9.3) Ethyl Cellulose

This material resembles p.v.c. in that it requires compounding to attain sufficient thermoplasticity for cable purposes. Until recently the plasticizers employed have not been entirely satisfactory for many cable purposes, but there has been much improvement in this direction. The material has good electrical characteristics, superior to p.v.c., and it is flexible at low temperatures, but on the other hand it is not resistant to solvents and it is inflammable.

(9.4) Polyisobutylene

By itself, this material has never been successfully used as a cable insulant, but it has proved to be a most useful compounding agent, and as such has figured in compounds with polythene, polystyrene, rubber, cyclized rubber, etc. The lower-molecular-weight types are liquid but the higher-molecular-weight types (60 000 to 100 000) are solid and rubbery. They have become

familiar as Vistanex (U.S.A.) and Oppanol (Germany). P.i.b. is less thermoplastic and more "rubbery" than unvulcanized rubber. It has high resistance to ozone and imparts this characteristic to compounds containing it. On the other hand it is broken down (de-polymerized) by sunlight. The temperature range of its elastic properties (− 70° to + 180° C) is the widest known. Its electrical properties compare favourably with polythene and polystyrene, and as a compounding material it has been employed very considerably for cables working at high frequency. The greatest defect of p.i.b. is the cold flow, which is pronounced.

P.I.B. has been largely employed as a compounding material for rubber mixes (see Longman[15]) to induce resistance to ozone, acids, alkalies, common salts, and heat. This emphasizes an aspect of the use of thermoplastics which has not been dealt with in this paper, namely the part that can be played by thermoplastics in modifying rubber mixes and thereby strengthening the position of rubber in any technical competition which may arise between rubber and thermoplastics.

(9.5) Polystyrene

This material also has not been employed by itself as a cable insulant, although it has had quite considerable use in combination with rubber and/or polyisobutylene. It suffers from the defect that it is comparatively brittle at ordinary temperatures and requires the development of a suitable plasticizer to bring it into the sphere of normal thermoplastic cable insulants. It becomes extremely rubbery at about 80° C. It is of course a component in Buna-S (GR-S) which is a co-polymer of butadiene and styrene. It may thus be claimed that thermoplastics are also assisting in building up the position of synthetic rubbers in the competitive field mentioned above. Electrically, polystyrene is in the polythene class.

(9.6) Nylon

Although this material is extrudable at very high temperatures, its principal contribution to the cable field is as an enamel for magnet wires or as an extremely strong filament (textile) for braiding. Its principal merit is high abrasion resistance, and it may be considered solely as a protective material.

(9.7) Cellulose Butyrate Acetate

This material is used considerably in the United States, usually as a tape insulant and particularly for automobile cables.

(9.8) Polyvinylidene Chloride

This resembles nylon to the extent that it requires a high extrusion temperature and that by "drawing down" it can (by orientation of the molecule) be given a greatly increased tensile strength. It cannot be easily plasticized. Vinylidene chloride can, however, be co-polymerized with vinyl chloride,[16] and some interesting materials in this series are being developed.

(10) P.V.C. VERSUS RUBBER

It is unfortunate that topical discussion tends to set up a competition between rubber and thermoplastics. It is argued on the one hand that, with the growth of thermoplastic production, rubber as a cable insulant and/or sheath will be restricted to a few special uses. On the other hand it is argued that thermoplastics, in view of their plastic attributes, will always be inferior to rubber which, in virtue of its vulcanization, becomes "set" and elastic. The truth in all probability lies beween these two extremes, i.e. both rubbers (including synthetic) and thermoplastics will play a part in future cable development.

While rubber is an extremely versatile material, it has a number of disadvantages: it is attacked by oxygen, ozone and sunlight. Minute amounts of common materials such as copper and manganese make it break down readily. For this reason, all copper wires used in rubber cables must be very adequately protected by tin or lead. It is also attacked by strong acids and is swelled by oils and solvents. It is highly reactive chemically, owing to its unsaturated chemical character. The chemical inertness of a thermoplastic such a p.v.c. has been well expressed by Chapman.[13] Polythene is resistant to chemical attack; the characteristics of polyisobutylene have been dealt with above.

Rubber possesses, however, excellent electrical characteristics and high mechanical strength. Because of its versatility, rubber has been adapted to a vast variety of cable and wire applications and its weaknesses have been masked to a great extent by the ingenuity of the cable engineer. No one thermoplastic can cover the range of applications to which rubber has been adapted. For each specific application, however, it is probable that a thermoplastic or thermoplastic compound can be devised which will compare favourably with rubber. P.V.C. has undoubtedly proved that it is an adequate substitute for rubber in many cases; other thermoplastics such as polythene would undoubtedly have exhibited similar replacement value if supplies had been available. In any event, both p.v.c. and polythene have made possible the manufacture of cables and wires with important characteristics which could not be equalled by rubber.

It is thus a reasonable prophecy to say that, when the war is ended and free competition in respect of materials on an economic basis is again in force, thermoplastic materials will be found to have taken up a definite and useful position in the cable field. It is not reasonable, however, to assume that rubber will be largely eliminated; further the case of thermoplastics versus synthetic rubbers has still to be examined in the light of a growing experience of both types of materials.

(11) CONCLUSION

The main object of this paper was to review the present position of commonly used thermoplastic materials such as p.v.c. in the cable field and to indicate the methods of evaluation of suitable insulating and sheathing compounds. The evidence leads to the conclusion that suitably selected thermoplastic compounds can produce satisfactory wires and cables whose characteristics are such that the corresponding rubber cables can be replaced by these thermoplastic cables. Oxidation need no longer be considered as the predominant factor in determining life; there are still restricting factors which prevent thermoplastic cables from being worked at temperatures appreciably in excess of those suitable for rubber cables, but these factors are of a different nature and may be countered by development and design along lines which would be impracticable for rubber.

The cable engineer has acquired a range of alternate materials which, while they present problems of their own, promise interesting solutions for some existing problems.

A period of accelerated development of wires and cables of compound characteristics must inevitably ensue as soon as free choice, on an economic basis, of such materials is practicable.

The authors wish to point out that this paper has been written on behalf of the Cable Makers' (War Emergency) Technical Committee which represents the combined technical staffs of the entire cable industry. They must therefore acknowledge the immense assistance derived, in compiling the paper, from the free access afforded to the technical data which have in recent years been accumulating rapidly in the laboratories and technical departments of the industry.

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DISCUSSION BEFORE THE INSTALLATIONS SECTION, 10TH FEBRUARY, 1944

Mr. G. O. Watson: It is a matter for speculation to what extent p.v.c. cables will continue to be used in the post-war era. In many respects they may be considered superior to rubber, e.g. in their fire-resisting and non-ageing properties, and their resistance to oils, chemicals, etc.; but it is their thermoplastic properties which will determine their continued employment.

The authors say little on installation problems, and although Section 8 is headed "Uses and Installation of Cables," it gives no information of unsuitable methods of installation. Who are the experts whose advice on design we are advised to seek, and if the information is available could it not have been included for the benefit of the Installations Section?

Will the authors give a schedule of substances commonly met with in commerce which will attack p.v.c., and also those against which it is proof? Such a list even though incomplete would be a useful guide. The chief disadvantages of p.v.c. are with regard to its thermal properties. So far the only official specifications as to quality are the Government Department Electrical Specifications (G.D.E.S.). The authors have referred throughout the paper to G.D.E.S.18, and I would recommend anyone who contemplates using this material to study this specification, as the tests and standards to which this material is now being made form a good guide to the uses for which it is appropriate. G.D.E.S.16, referred to in the paper, is a secret document.

While the governing feature in Service requirements is the ability to withstand very low temperatures, the standards in this respect are much below industrial requirements, even in cold stores. Section 7 confirms that Service requirements have been the overriding consideration, and states that in the United States the electrical resistivity and the resistance to thermal deformation of this product are higher than over here.

The p.v.c.-insulated cables now offered in this country are unbraided, and the addition of braiding in order to minimize volatilization of the plasticizer and improve resistance to thermal deformation, as is done in the U.S.A., deserves reconsideration. I understand that the maximum range between cold cracking and softening temperature is about 90° C. Will it be possible to produce a compound with a cold crack of, say, — 10° C and a correspondingly higher softening point? It is the softening point which gives most concern. There is always the danger of contact with hot water or steam pipes, radiators, etc., which may be inadvertent or has not been avoided in the layout. If, owing to accidental overloading, the cable becomes heated to, say, 120 or 130° C the conductor may sink right through the insulation under its own weight or by tension on the conductor. Figs. 1 and 7 give one some idea of these characteristics; additional curves in Fig. 1 showing the position after 12 and 36 hours and extended to 120° C would be interesting.

The effects of connecting the cables to the terminals of switchgear have also to be considered in relation to the temperatures permitted in the relevant B.S. Specifications, namely 88—1939, 861—1939 and 159—1932. For fuse terminals carrying above 150 amp a maximum temperature of 70° C, and for currents of less than 150 amp a maximum temperature of 60° C, is permissible, based on ambient temperatures not exceeding 25° C in both cases. For air-break switches carrying above 100 amp the temperature rise is 30° C with a peak ambient of 40° C, giving a corresponding total temperature of 70° C, which is the temperature at which the cables are tested under G.D.E.S.18 For contactors, B.S. 775—1938, no temperature is specified for terminals, but generally speaking the temperature of the contacts is much higher than with ordinary switchgear. For switchgear busbars the maximum total temperature for currents below 2 000 amp is 70° C based on an ambient temperature of 30° C.

After long experience with rubber we have established a few simple mechanical and electrical tests which, if applied by a reputable cable manufacturer, would more or less ensure satisfactory cables. With p.v.c., even with the tests prescribed, the chemist can still change the composition and give us a cable in which the plasticizer may be liable to become leached out or evaporated as indicated in Sections 4.3.1 and 4.3.2, and a cold-flexibility test seems to be essential for controlling this feature. The accelerated ageing tests as applicable to rubber cannot be applied to p.v.c. to give comparable results.

With regard to installation problems the authors do not state the current-carrying capacity. It is generally taken that the same rating may be used as for rubber, but it is not safe to assume this. The E.R.A. has made some tests which might usefully be published with this discussion.

The use of p.v.c. in place of lead as a sheath has been proposed. I believe this was the first use to which the material was put in Germany. The effect of decomposition when cables are overheated to destruction must also be considered, for I understand that hydrochloric acid and chlorine are products of such decom-

position. To what extent would the emission of chlorine be serious in the event of fire involving large quantities of p.v.c.?

With reference to the thermoplastic conditions, care should be taken when installing these cables or handling under very cold conditions, e.g. in transit. The paper does not state that p.v.c. has a considerable temperature coefficient of resistance and some information on this point would be of value. When p.v.c. is clipped in position, the clips should not be spaced too far apart as this gives too great a concentration on the clips and excessive sagging which might eventually cause deformation and breakdown.

Although I have concentrated on some weaknesses of p.v.c. and the precautions which prudence dictates, nevertheless for 99% of ordinary building requirements p.v.c. is an admirable material and in my opinion it is in many respects as good as, if not superior to, rubber.

Dr. P. Dunsheath: This important paper demonstrates the heavy debt which electrical engineering owes to the chemist, and the wide knowledge of chemistry now required by electrical engineers, particularly in the development of cable making. It constitutes a notable example of the combination of physics, chemistry and electrical engineering.

An electrical engineer casually reading the paper might be deceived by Section 3 into ignoring the vast amount of work which lies behind the brief reference there to the polymerized structure of the substances now being employed by cable makers, although the electrical engineer himself has contributed very largely as, for example, through the electron microscope. As the result of this work we are now able to discuss not only the structure of these complex molecules, but also the extent to which the structure contributes to the electrical and physical properties of the finished cable.

It is noticeable that in one or two places in the paper, the authors have issued a note of warning against prejudicing the progress of these plastic materials by ignoring difficulties which still exist. They have been very frank in putting before us a clear statement of the problems still to be solved; the paper contains so much information that a studious reader might almost draft a specification for making p.v.c. cables. I support the authors in their suggestion that the cause of progress would be ill-served by any over-simplification of the problems. Attempts to impose on the manufacturers, specifications which in any way restrict their development activities would only stifle initiative.

While much has been done already to standardize materials and to control processes, much progress will follow during the next few years. In the case of rubber cables, reasonable performance tests agreed between user and maker, combined with the employment of highly-skilled personnel in the industry, gave us a very successful record of performance. There is no reason why, in spite of all the new problems involved, thermoplastic cable should not give us every bit as good a record.

Dr. G. E. Haefely: The paper is a good example of close co-operation between the chemist, the plastics technologist, and possibly the user. My remarks will be limited to the vital question of raw materials. I have followed with more than sympathy the continued efforts to convince the country of the necessity of putting down more chemical plant and utilizing to the utmost the raw materials abundant in this island. How can this country otherwise hope to compete in the world market? As a Swiss I cannot resist the temptation to draw a parallel with my own country. Switzerland, with the great assets of beauty on her surface, is particularly lacking in such materials as coal or petrol from which the synthetics are derived. In order not to be too dependent on other countries, Switzerland has had to exploit her water power to the utmost extent of her financial capabilities. Without this foresight half a century ago, she would not have survived the first world war and could not hope to continue to play her appropriate part in the future.

Mr. G. Smith: In some tests on installed p.v.c. cables, we found no trouble in a building wired ten months ago on the surface, using turnbuckle clips. In another building wired six months ago on the surface, using insulating saddles secured by two pins on either side of the cable, there were two circuits with cable dielectrics of 0·65 and 1 mm radius respectively. A test after three months gave insulation values of 16 000 ohms for the thin, and 12 megohms for the thicker, insulation. Several saddles had pinched the cable, for when the pressure was removed the resistance rose to 15 megohms, later still to 16 megohms. Parts of the wiring had been covered with distemper between the two test periods.

The next test was on a slab, 7 ft by 3 ft, covered with five different kinds of plaster in which p.v.c. cables were embedded. Resistances were measured in August and November, 1943, and just before this meeting. The readings, all between poles, were infinity on each occasion. This slab is inside a building, and the cables are maintained at 230 volts to earth.

In another test a length of two-core "tape" pattern cable was left for seven months in a room maintained at a temperature of 70° F (21° C) and 77% relative humidity. The insulation resistance between cores was measured each month, and infinity readings were obtained at each test. A similar cable was immersed in water for one hour at 20° C, and, after five minutes' electrification at 500 volts d.c., gave a resistance of 6 400 megohms per thousand yards between cores.

The authors refer to the experience yet to be gained in actual service. Would they indicate the kind of observation required, so that different experiences can be co-ordinated?

A variant of p.v.c. of low plasticizer content appears sufficiently hard to give mechanical protection. A minimum temperature of − 15° C has been specified as suitable for the interior wiring of buildings in this country, but the views of the authors and users on a suitable temperature range for general installation work would be useful.

Mr. S. W. Melsom: The paper provides a particularly full and clear exposition of the chemical side of the subject, although there may be some disappointment that it contains only one paragraph, mostly of a negative nature, on the question of installation. Careful study of the paper, however, will probably show that there is much information of value which, together with further direct information from cable makers' representatives, will prove of the utmost value to the Wiring Regulations and Codes of Practice Committees, at present engaged on various aspects of the installation regulations.

The uses of p.v.c. are many, and I should like to mention one in particular: miners' cap-lamp flexibles. The life of rubber cables of this type is short, mainly owing to the chemical action of perspiration. P.V.C. flexibles have been tried and, although some slight shrinkage and cracking has occurred, the cables have outlasted two rubber cables of similar type and on similar duty.

The authors have mentioned the important question of shrinkage. I am inclined to think these difficulties have been overrated and that they will largely disappear with improved manufacturing technique. It is, however, most desirable that further information on this subject should be published as soon as possible.

In Section 8.2, the authors mention the possibility of shrinkage when the conductor is soldered. This again, I believe, need give no serious concern. Soldered joints are unusual in installations, particularly for the smaller conductors; with the larger conductors they are mainly at the ends where the bare conductor is passed through a bush and where any shrinkage can be made good with lappings of insulating tape.

The section headed "P.V.C. versus Rubber" may be a chemical controversy, but is hardly one for installation engineers. There is far too much tendency to consider p.v.c. in relation to rubber, whereas I think it should be considered on its own merits. Installation engineers already deal with materials as widely diverse in their characteristics as paper and rubber, and they know quite well how to arrange the conditions to suit the particular type of material. I have not the slightest doubt that they will consider p.v.c. from the point of insulation-worthiness and install it under suitable conditions, rather than expect it to comply with every condition which rubber will meet.

The resilience of rubber is a quality which, as far as I know, is not approached by any other material, and it would, I think, be unfair to expect p.v.c. to comply with any installation conditions based on the resilience of rubber. It is, of course, possible that ultimately p.v.c. will not prove a satisfactory substitute for rubber, but, on the other hand, it can only have a fair trial under installation conditions suiting its own inherent qualities.

Apart from the question of final merit—and rubber may last something like 20 years—the post-war use of p.v.c., like that of many other things, may be a question of economics. If rubber is available at anything like its old price, with p.v.c. at a much higher price, undoubtedly most of the cable will be rubber-covered on this score alone.

I am still of the opinion I expressed to the Transmission Section some two or three years ago, namely that after the war there will continue to be a use for p.v.c. for certain purposes, but that the full extent of its use will depend largely on the experience now gained.

Mr. P. S. Cattle: If we have been using and improving rubber as an insulator for more than forty years, we shall not settle down to p.v.c. in one year. We require of p.v.c. that it shall be an inert insulator electrically and mechanically as nearly perfect as possible; also it must be elastic, have a long life, and be able to withstand variations of temperature and atmosphere.

Are plasticizers always inert, or do they evaporate during life or under varying temperatures? If loss takes place and the p.v.c. is under continued strain or vibration, is it liable to crack in five or ten years' time? A somewhat similar effect occurs with vulcanized rubber under fluctuating conditions of temperature and light radiation. When using p.v.c. of a hard type the cost of erection has been considerably increased when working in a temperature of 40° F.

When bending v.i.r. cable the central axis is the point of bending and the rubber tends to flow round the cable. With hard-grade p.v.c., however, there is definitely no flow at a low temperature. There is also the risk of p.v.c. being under tension when bent.

On stripping p.v.c. insulated cable of roughly the same hardness as copper with an ordinary knife, the depth of cut cannot be controlled. Examination of the cable with a magnifying glass shows that if a cable is nicked by the knife in any way, there is always the risk of a subsequent break in the conductor at that point. The toughness of the p.v.c. insulation is such that a small amount of insulation laid between the strands calls for considerable strength to break the p.v.c. away from the conductor. In age tests, cables should be tested at overload and by cooling. The heating of a cable may cause some evaporation of plasticizer. I heated a piece of cable and after a time found some spots on the surface. Was this due to the plasticizer evaporating?

Further, with standard p.v.c. cables we found that the present finish does not allow the cables to be drawn independently in and out of the conduits. They cling to each other and also to the internal surface of the conduit, especially round a small bend or sett. With present cables it is practically impossible to rewire a building or make alterations after a time.

I recently tested p.v.c. spaced ($\frac{1}{2}$ in) twin conductors, 2–3/·036, the current in this circuit being limited to 30 amp 230 volts 50 c/s. The conductor was fixed vertically to a piece of damp, charred softwood. An arc was struck, maintained, jumped across again and went out. The insulation did not catch fire, but the arc could have fired anything inflammable in close proximity.

Mr. J. Veit: It was mentioned that polyisobutylene is most used with mixtures of rubber or other thermoplastics. In Germany, lead-covered cables insulated with polyisobutylene have been made, with a glass fibre braided over the isobutylene. These cables will withstand very severe conditions. Polyisobutylene is one of the very few materials which will withstand a temperature range of − 70° to + 150° C.

The importance of polythene must be emphasized, not only for high-frequency cables for which it is used, but also for any high-voltage cables. Marked developments and changes in the manufacture of high-voltage cables may be expected.

The authors state that a certain loss of plasticizer can be prevented by placing a braiding over the insulation. Does this refer to any braiding impregnated with any material, or only to a textile reinforcement made in a certain way? Theoretical considerations indicate that if the braiding is impregnated with a p.v.c. cement, a thin film on top of the insulation is produced, which will prevent the evaporation of plasticizer. Does this also happen with one of the compounded braidings?

Where p.v.c.-covered wires have to be soldered, some specifications demand a reinforced wire. A textile reinforcement can be made either by putting an impregnated braiding over the insulation, or by using a cotton lapping or braiding as a separator between the conductor and the insulation. This may have a further advantage when the wires are exposed to high temperatures. The paper indicates that the resistance of p.v.c. drops with temperature; I think this loss can be regained by the second dielectric afforded by the cotton wrapping, and products, reinforced either inside or outside, can be considered for special applications as offering very great improvements in thermal resistance and mechanical strength.

Mr. H. J. Horn: The development of p.v.c. cables has received encouragement from those responsible for electrical installations in aircraft, because this form of sheathing assists materially in overcoming certain mechanical difficulties associated with cellulose. The resistance of p.v.c. to water, petrol-vapour and oil also makes its use desirable.

The limited space available in aircraft, and the numerous situations necessitating sharp turns, call for a cable of extreme resilience, coupled with toughness. The sheath must be unaffected by extreme variations of temperature from 70° C to − 70° C, and, whilst sufficiently flexible, must also be capable of efficient service within that temperature range. We have for some time employed p.v.c. conduits in aircraft to carry the cables, in place of flexible metallic conduits.

In the first installations, the amount of plasticizer was adjusted to provide a rigidity similar to that of the metallic sheath being replaced, and the results were not very successful. This rigidity was necessary to guard against damage to cables and soldered joints when a sudden strain is placed on the conduits. "Concertina-ing" the conduit back on itself at low temperature for servicing work was found impracticable, and a softer grade of conduit had to be adopted and more closely-spaced metal clips used.

As to the use of p.v.c. as a dielectric, in view of the extremely congested nature of an aircraft installation, each item of equipment has to be of the smallest practicable dimensions, while temperature and atmospheric conditions also have to be taken into account. At times all the electrical equipment is wet, hence aircraft cables must maintain a high insulation resistance.

Hitherto, we have regarded with disfavour the use of p.v.c. as a dielectric for cables, preferring to use a rubber dielectric. The necessary depreciation, however, of the rubber permitted for this purpose has progressively brought down insulation resistance figures to a point beyond which it is inadvisable to go. If a p.v.c. with a suitable insulation and physical characteristics is produced we shall welcome its introduction as a dielectric.

Mr. C. King: As a rule the contractor does not find it practicable to use more than one grade of cable on any particular building job, and as the temperature range of the present C.M.A. standardized product is only 0° to 135° F, the use of p.v.c. for most standard appliances appears questionable. At one end of the scale is the working temperature of the terminals of deep-freeze refrigerators, and at the other end those of tungsten lamp-holders, irons, kettles, toasters, water heaters, cookers, air heaters and so on. Most of these are outside the permissible temperature range, particularly having regard to the contact troubles which develop and the practice of eliminating flexibles by taking the cables direct to lampholders. The same applies to p.v.c. exposed without a metallic enclosure to the open sun. Allowing for the flow of current to cause a rise of only 30 deg. F, on sunny days the combined temperature may be about 150° F.

On drawing cables through conduits they become twisted, causing stresses which appear undesirable with p.v.c. cables, particularly if they are unbraided. The same applies to the weight of p.v.c. cables when hanging loosely in long conduit drops.

Since deformation of p.v.c. under pressure is not instantaneous, will this mean the continual tightening of cord grips to stop fittings falling down, and will such attention be eventually rewarded by short-circuits? In cleat wiring, clips and similar fixing methods, how will the good craftsman react to the loosening of the cable fastenings brought about by this cold-flow disability?

Owing to the effect of air flow on the evaporation of the plasticizer, should the ends of conduits be sealed, and should p.v.c. cables be used on draughty and warm appliances, such as unit heaters?

The dielectric resistance of p.v.c. seems to vary between 10 and 100 megohms per 1 000 yd, whereas with pre-war v.i.r. the value was between 2 000 and 3 000 megohms.

The authors infer that in well-built conduit systems unbraided p.v.c. may be used, but how can one tell whether a conduit system is well built? If the authors are thinking that an extended immersion of p.v.c. in water may be unfavourable, such as loss of plasticizer and dielectric resistance, then since dips into which water will settle can hardly be avoided even on horizontal runs, another reason must be added to those deprecating the use of unscrewed joints in concrete or cement screedings, since of the present devices in use the well-painted screwed socket joint reinforced by a lock-nut is the only one which will keep the water out.

The corrosion question is one of economics, and v.i.r. cables may continue to score in most cases because of their cheapness. The present cost of p.v.c. is between 19 and 45% higher than that of v.i.r. Elasticity has a definite economic bearing. Size for size, unbraided p.v.c. cable is smaller than v.i.r., but owing to its stiffness a greater number cannot be drawn through conduits.

The trouble with v.i.r. is that it is a chemically unsaturated substance and needs alliance with other things to render it more resistant to heat, chemicals and radiation. For corrosive situations a synthetic coating, such as p.v.c. over v.i.r., forms an excellent combination, particularly as this utilizes the superior dielectric and elastic properties of v.i.r.

Because of the cold-flow disability of p.v.c., I think the more rubber-like materials, such as Neoprene, have a much more promising future.

Mr. F. C. Raphael: I take a different stand from my fellow installation engineers on this question of using thermoplastic cables. We have to anticipate a period during which insufficient rubber will be available to wire with v.i.r. cables all the buildings that will be required, and I should be perfectly ready to accept thermoplastic cables and to make a good job with them. I am very glad to have the information contained in the paper, and my main criticism is that it is set out in such a way as to give the impression that these cables are only in an early experimental stage. That is not the case. The cable now offered, so far as one can gather, has distinctly fewer disadvantages than v.i.r. cable, most of which were only gradually realized after its original introduction, such as its secular change, its only partial waterproofness and its susceptibility to rust effects, etc. Cold flow has also been a source of trouble with the rubber cable. Under a constant pressure the rubber will flow away and eventually leave a bare conductor.

These troubles have led to progressive improvements, and the same will happen with thermoplastic cables, except that the difficulties will not be of the same magnitude as with rubber. For instance, if we extend the low-temperature flexibility unduly we must sacrifice other qualities. For building work this very low-temperature flexibility is not needed, and if the other qualities can be increased by dispensing with it, it simply means that we must not be satisfied to make all our cables in accordance with G.D.E.S.18. This specification can apply where we know that extremely low temperatures will have to be experienced, but a different specification, with better qualities, which are lost by excessive incorporation of the plasticizer, will be needed to conform merely with the ordinary temperature requirement.

The authors' figures for resistivity do not appear so low that The Institution's Wiring Regulations Committee or the Codes of Practice Committee need have worried to decide that a quarter of the insulation resistance formerly laid down in the Regulations for the whole installation has to be accepted. A cable of, say, 10 megohms per 1 000 yd will not affect the insulation of the complete job.

Mr. D. B. McKenzie: I am glad to learn that the authors do not think of these synthetic materials only as substitutes for rubber, but have considered them as offering special properties of their own which are not possessed by natural rubber.

Although much research work has already been carried out in this field, and in the case of p.v.c. many hundreds of plasticizers have been tried, there still appears to be a very large field open for fundamental research work to improve the electrical properties of p.v.c. and still retain their good physical properties. The authors give a very conservative maximum working temperature of 55–60° C. Do they, therefore, consider p.v.c. to be unsuitable for tropical use—although in Section 8 they state that in America ships' cables are rated at 90–100° C?

Reference is made to G.D.E.S.18, in which the test requirements for p.v.c. compounds are given. This specification is, however, a material specification, and does not cater for tests on a finished cable. Do the authors, therefore, consider that in the processing of p.v.c. during the manufacture of a cable there is no change in the properties of the material? It seems to me that it is very necessary in preparing specifications for p.v.c. cables to refer to G.D.E.S.18, but, in addition, to include performance tests on the finished cables.

In Section 5.5 the authors make a very interesting statement that the abrasion resistance is of a somewhat higher order than average t.r.s. Although this may be so, the tear resistance is lower, and this factor should be borne in mind when using p.v.c. sheathed cables.

On reading this paper, I gained the impression that little or no difficulties were encountered during the early development stages.

This is, of course, not the case, and some insight into the troubles experienced during this period would be of interest.

Mr. W. A. McNeill: As a representative of a switchgear firm which has used p.v.c. cable for small wiring for nearly two years, I should be interested to know how grade 1002 would behave under adverse conditions. What is the effect on flexibility when the cable is subjected to rapid alternations from tropical to arctic conditions, such as may be encountered in aircraft or on board ship?

In ageing tests, the authors do not mention any contraction which may expose the conductor. Tests have shown that such troubles might be met with sleeving, but are unlikely with p.v.c.-insulated wire where there is a greater tendency to reduction in diameter than to contraction. Dimensional changes may be partly due to the release of initial strains set up in manufacture.

My own experience has not altogether borne out the claim that the effect of colour pigments is negligible. The contraction with blue was about 50% of that obtained with red and yellow.

The claims made by the authors regarding concentricity are not altogether confirmed by experience, and it has been necessary to check carefully incoming materials for eccentricity.

Would the authors give their opinion on the use of p.v.c. in conduits attached to outdoor switchgear where the surface of the conduit is directly exposed to the sun?

Mr. E. E. Hutchings: The maximum safe working temperature of 57° C for unbraided p.v.c. cables allows a margin of 12° C over the ambient limit above which these cables may not be installed in ships. This corresponds closely to the permissible rise, assumed the same as for rubber cables. The margin of safety is small, and braiding would appear to be a very desirable precaution in all ships' cables in view of the continual movement they experience.

Data on the thermal resistivity of p.v.c. are not given in the paper; elsewhere the value of 2000 thermal ohms/cm cube has been quoted. E.R.A. tests on two samples of p.v.c. cable from the same maker, indicated thermal resistivities of 1 250 and 1 520 for 0·06 and 0·01 in^2 conductors. Thus for the same dimensions and temperature rise, ratings would be lower than for rubber-insulated cables; we found a 10% reduction in one installation investigated.

In view of the critical effect of the pigment in p.v.c. on its electrical properties, it would be interesting to hear whether painting the cables, which is common practice on ships, is likely to affect them seriously, and whether any special precautions should be taken regarding the nature of the paint used.

Abrasion resistance has been studied by the E.R.A. and satisfactory tests have been standardized. The method is fully described in E.R.A. reports.

Mr. S. F. Follett: The authors have quite rightly refused to comment on the economic aspect of the plastic compounds, but they do not appear to have mentioned one economic advantage of the plastic cable, namely its relative simplicity of construction in certain cases. They mention the application of p.v.c. by longitudinal methods, and suggest that the need for braiding and heat treatment is a disadvantage of the material. Are these not disadvantages of the method and not the material? The normal method of application is by direct extrusion, and the longitudinal method should be considered only as an emergency method, although it is useful under the present conditions.

The somewhat unusual figure of 57° C has been mentioned as the limiting temperature. Has this figure been determined by consideration of plasticizer loss or thermal deformation? If the former criterion is the limiting factor, then for relatively short-life applications could not a higher temperature be permitted? Presumably, the temperature referred to is the ambient temperature and does not include any allowances for increased temperature due to current loading.

Caution should be exercised in hardening the cable, since this will reduce the present excellent flexibility of the p.v.c. sheath. A fair amount of cold flexibility is also required for installation even under normal conditions. For flexible cables, the depreciation of flexibility with ageing, with consequent loss of plasticizer, should also be considered. Loss of plasticizer with heat or ageing, as well as relief of stress on heating, will cause shrinkage; this should be considered in the installation of p.v.c. cable.

Generally, the paper emphasizes the difficulties caused by using plasticizers in p.v.c. compounds. While further work on plasticizers is obviously desirable, some part of the energy devoted to the exploration of new plasticizers should be expended on examining inherently flexible materials, such as polythene and polyisobutylene.

Mr. J. G. Jessel: For p.v.c. cables used in normal building, the question of flexibility is not so important as other aspects, such as high insulation resistance and good mechanical protection, and it is only for drawing cables into conduit that the question of extreme flexibility becomes so important. By using less plasticizer we get a cable with improved electrical and mechanical properties at the expense of flexibility. A cable with these properties could then be used without conduit and would make a very good wiring system for small domestic dwellings, especially where a ring main for sockets is contemplated, thus eliminating many of the difficulties attendant upon wiring a ring main in conduit.

Mr. D. C. Bacon (*communicated*): The embargo on the use of p.v.c. cable for general lighting and power purposes was not lifted until April, 1943, and, owing to the stocks of v.i.r. cables held by factories, there has, up to the present, been little opportunity for factory electrical engineers to compare the performance of p.v.c.-insulated cables with that of v.i.r.

In the factories with which I am concerned, it is necessary to take special precautions to avoid, as far as practicable, the occurrence of electrical breakdown which could give rise to undue heating or exposed sparking. All cables inside the buildings are carried in screwed conduit and, for the lighting installation, dust-tight dispersive reflectors are screwed to conduit drops.

In view of the inflammability of war-emergency v.i.r. cables, I had hoped to use p.v.c. cable for future lighting installation work and was given to understand that unbraided p.v.c. cable would prove satisfactory at temperatures up to 70° C. The authors, however, state that the maximum safe working temperature of unbraided p.v.c. cable is 57° C, and this upper temperature limit is considerably exceeded in the conduit drop adjacent to the dust-tight lighting fittings, to which I have referred. The temperature in this drop, taken on the end of the cable insulation at the back of the lampholder is 60° C for a 100-watt lamp and 65·5° C for a 150-watt lamp with an ambient air temperature of 19° C. At certain times, the temperature of the cable ends will rise to 70° C and, although these ends are not subject to any deforming pressure, it would appear that there would be shrinkage and longitudinal splitting of the p.v.c. which would introduce the risk of electrical breakdown.

It is well known that at such temperatures v.i.r. ages very rapidly, but so long as the brittle v.i.r. on the last 3 in or so of cable is not disturbed I think it constitutes a smaller risk than shrunken and split p.v.c.

It would be helpful if the authors would give their opinion as to the amount of shrinkage and splitting of unbraided red and black p.v.c. which occurs when the temperature is maintained between 65° C and 70° C for 24 hours a day continuously; whether this shrinkage is progressive; and whether, under these

temperature conditions, it would be quite safe to install braided p.v.c. cables.

Mr. F. Meyer (*communicated*): The authors have done the industry a service in that the user should now appreciate the difficulties of the manufacturer, and the engineer become more tolerant towards the seeming inconsistencies in thermoplastic cable insulation.

It is a pity that the standardization of p.v.c. compounds was left so long after their general acceptance as a cable insulation, because those engineers who have been trying to standardize certain grades which seem to suit their particular usage are thrown back to a position not much in advance of the introduction of p.v.c. cable, i.e. they have to start all over again trying to fit grades to usage.

It is interesting to note that the authors consider that as p.v.c. is one of the easiest materials to extrude, very fine results can be obtained in respect of concentricity, thin walls, etc. As a user, I have found that quite a number of samples I have examined do not bear out this contention.

In using p.v.c.-insulated cable, as leads on coils, armatures, etc., I have found that where these leads have been covered with varnish during dipping or impregnation processes they have withstood elevated temperatures without becoming brittle, much better than leads which have been kept free of varnish. The authors confirm my view that this was due to preventing the evaporation of plasticizers.

In spite of the excellent abrasion resistance of p.v.c.-insulated cables quoted, it has been my experience that where such cables have to be taken round sharp corners by bending and through conduit, trouble is experienced unless the cable is braided.

It is unfortunate that the C.M.A. did not realize the potentialities of p.v.c. as a cable insulation before they were compelled to recognize it as a substitute for rubber. In spite of what has seemed on their part almost an objection to the development of thermoplastics for cable insulation, there appears to be no doubt that such cables will enjoy extensive post-war use.

Dr. J. L. Miller (*communicated*): I welcome the paper, not only for the detailed information it provides, but also because it gives a well-balanced picture of thermoplastic materials and their place in the general sphere of cable insulation. Many users have perhaps hitherto failed to appreciate that p.v.c. is a material with properties capable of variation over a wide range, according to its make-up. I feel, therefore, that the authors have been wise in stressing this point and in drawing attention to the restrictions placed on the choice of compounds for general civilian needs by the present supply position.

I must, however, criticize one point. The authors in making a very brief reference to nylon, dismiss it, rather summarily I think, "solely as a protective material." This, of course, is not in accordance with the facts because, in enamel for magnet wires, nylon does form the basis of a film covering which can surely claim description as an insulant. From the data quoted in the paper, the electrical properties of nylon itself compare very favourably with those of, say, the No. 1002 p.v.c. compound. Electric strength is but a little lower. Resistivity is of the same order, and both permittivity and power factor are much lower. This clearly brings it within the class of insulating materials in its appropriate sphere.

For wire enamel the electrical properties of nylon are still further enhanced by modification with thermosetting resins. For instance, dielectric strength of the order of 1 500–1 700 V/mil is attained in production. In fact, the outstanding properties of toughness, flexibility and abrasion resistance of the material should not be allowed to overshadow its electrical properties. Incidentally, the combination of thermoplastic and thermosetting materials is of interest in that composite properties are obtained. As an example, plastic deformation under heat and pressure is much reduced. Like many other wire-covering materials, however, the nylon-based enamels are hygroscopic, and impregnation after winding is therefore usual.

In regard to the future trend of wire design, it must be remembered that in the paper the authors are dealing with the very restricted choice of nylon now available in this country. The name nylon covers a variety of condensation products of certain diamines and dicarboxylic acids, and when free choice is available we may secure even more interesting polymers. Nylon, therefore, is already valuable as a wire insulant. The future may see still further improvements, and I wish that the authors had either omitted all reference to nylon or had treated it more fully. As it is, I feel they have quite unintentionally "damned it with faint praise."

Dr. A. Rosen (*communicated*): The opening sentences of the paper somewhat understate the position regarding the past use of thermoplastics in cables; not only is their use "not new," but it formed a very foundation stone on which the whole cable industry was subsequently built. Nearly a century ago Werner Siemens introduced his process for covering wires with gutta-percha and thus made the first practical underground cables. The paper does not deal at all with gutta-percha and other natural thermoplastic materials, and perhaps a more restrictive title such as "Synthetic Thermoplastic Cables" could have been chosen.

The curves in Fig. 8 showing the variation of power factor of p.v.c. with temperature are interesting. Considering for example compound No. 1002, the first part of the curve, 0–35° C, shows the peak which is characteristic of highly polar materials, and over this range a.c. hysteresis loss is the predominant factor. Beyond 35° C, the true conductivity becomes more important, and the curve rises steeply owing to the rapid increase of conductivity with temperature. The figure also shows that the critical temperature at which the true conductivity takes charge shifts with frequency, for with a given value of conductivity the power factor ($G/\omega C$) is inversely proportional to the frequency.

In Table 2 the permittivity of nylon is stated to be higher at 1 000 c/s than at 50 c/s. Other dielectric materials have a constant or falling permittivity/frequency characteristic, and further information on the anomalous behaviour of nylon would be welcome.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Dr. H. Barron, Mr. J. N. Dean and Mr. T. R. Scott (*in reply*): We would point out to Mr. Watson, and to the other contributors to the discussion, that installation technique must be evolved by the user, albeit on the basis of information supplied by the cablemaker on the characteristics and limitations of the cable. Section 8 was written on this basis. The Cable Makers' (War Emergency) Technical Committee is prepared to assist users in connection with specific installation questions.

Regarding chemical action, we would refer Mr. Watson to Chapman's paper (No. 13 in Section 12). Although G.D.E.S.16 is secret, it is general knowledge that its amendments govern standardized war-emergency grades of rubber compound.

Mr. Watson and others apparently think that only unbraided p.v.c. cables are offered at present. This is not the case. The unbraided variety, however, appears to offer considerable advantages for many installations, provided it can be shown that the omission of braiding does not cause undue shortness of life, soldering difficulties, pulling-in troubles, etc. We believe that in

the near future, with co-operation between cable maker and user, these points will be satisfactorily cleared.

There is obviously a case for a standardized compound of cold crack −15 to −10° C, and improved characteristics at the maximum operating temperature. Such a compound will be introduced as soon as circumstances permit. It is too much, however, to expect p.v.c. to meet temperatures of 120–130° C; thermal deformation is not the only deterrent. In switchgear terminals at 70° C, it is considered that the ageing and deformation of the few inches of cable adjacent to the terminal will not cause trouble provided the cable is satisfactorily designed and manufactured.

The selection of the best control test for the determination of ageing characteristics is a complex matter, but great progress is being made in testing technique and improvements in the present method are in sight.

The evolution of chlorine when p.v.c. is severely overheated is, of course, the basis of the fire-resisting property of the material. If the fire is serious enough to decompose the bulk of the p.v.c. it is probable that the corrosion, etc., arising therefrom will be merely a minor aggravation of the damage caused.

Fig. 1 gives the temperature coefficient of p.v.c. It does not appear worth while to extend this diagram to 120° C for the reasons given above.

We agree entirely with the points made by Dr. Dunsheath and by Dr. Haefely.

Mr. Smith has made a valuable contribution regarding the installation aspect. Records of this nature are helpful in checking performance and in drawing attention to details which require attention, e.g. the effect of saddles. Reduction of plasticizer and increase of hardness are desirable for many purposes, but the overall design of compound must be carefully studied.

We agree with Mr. Melsom on practically all points. Soldering is, however, important in certain cases where p.v.c. wires are used. Shrinkage can be neutralized, and further remarks on this are given below.

Mr. Cattle will, we fear, be disappointed, since the production of an elastic and electrically-perfect p.v.c. compound does not appear to be practicable. We suggest, however, that sufficient elasticity and a sufficiently high electrical performance for a great variety of uses will be forthcoming.

The majority of plasticizers are volatile, and some hardening and transverse shrinkage are bound to occur within the service life. We could expect the useful life, however, to be considerably in excess of five to ten years if the best plasticizers are employed in the correct proportions. We do not agree with reducing plasticizer content and increasing hardness so that flexibility at 40° F is impaired. Mr. Smith specified a minimum temperature of − 15° C for interior wiring; we consider this temperature to be a good basis for the formulation of a compound for this type of work. In the limit, with negligible plasticizer content, p.v.c. may behave during the bending of a cable in a manner similar to that indicated. A compound which meets G.D.E.S.18 will, however, behave differently right down to its specified cold-crack temperature.

Special methods of stripping have been investigated. It is impossible to give an adequate description here, but details can be obtained by the procedure indicated to Mr. Watson above. There may be difficulties in pulling-in unbraided p.v.c. cables, particularly if lubrication is not applied. Braided cables, of course, give results similar to those exhibited by rubber cables.

Ageing tests are carried out under G.D.E.S.18 at 82·5° C, which is in effect an "overload." As mentioned above, the cold-crack characteristic may or may not be the best control test. Mr. Cattle gives insufficient data of his heating test to enable us to diagnose the cause of the spots. In his experiment with arcing, it should be noted that the arc did not set fire to the cable.

We note Mr. Veit's remarks about lead-covered cables insulated with polyisobutylene. We still feel, however, that the material has many limitations. To prevent or impede the volatilization of plasticizer the braid must be compounded or lacquered. We cannot quite follow Mr. Veit's film theory, but would anticipate that a lacquered braid would produce similar results. It is preferable, however, to have compounds which age slowly when used unbraided. We believe that braidings are unnecessary, even for soldering. A composite dielectric obviously exhibits characteristics based on both components, but it is questionable whether cotton adds much to the basic overall dielectric characteristics of a p.v.c. cable. For most purposes, in the presence of moisture we should prefer a normal p.v.c. cable to a textile insulated conductor sheathed with p.v.c.

Mr. Horn emphasizes two important points, namely the necessity of keeping the flexibility of a p.v.c. compound up to a certain standard (with resultant limitations on the hardness) and the importance of distributing load as uniformly as possible, e.g. by closely spaced clips. We believe it should be possible, when circumstances permit, to raise the insulation resistance of p.v.c. cables to a standard high enough for the aircraft wiring referred to, even under humid conditions.

Since p.v.c. cables are rated at temperatures equivalent to those at which ordinary rubber cables are rated, we must infer that Mr. King is registering a plea for a type of cable which has hitherto not been marketed—one which will meet all conditions likely to be encountered in a domestic installation. The use of a high-duty cable throughout an installation appears to be somewhat uneconomic. Technically such a cable is, however, just as likely to be designed on a plastic basis as on a rubber basis, judging from current knowledge.

Mr. King misquotes our statement regarding conduits in which unbraided p.v.c. cables may be used. Our specification is "modern and well constructed." We are not perturbed by the water aspect; loss of plasticizer and of insulation resistance will be negligible. The main point is that if dimensions and cost are to be reduced by omitting braiding, some care must be taken to give the unprotected p.v.c. a reasonable passage during pulling-in operations. The more plastic-minded the user becomes in this respect, the lower the standard of "well constructed" may be set.

Mr. King is obviously unduly worried about cold flow, evaporation of plasticizer and low insulation resistance. There should be sufficient elasticity in a standard p.v.c. compound working within its prescribed temperature range to prevent any of the troubles mentioned. Since many Service p.v.c. cables (unbraided) are giving satisfaction in open positions where they are exposed to wind and sun, the loss of plasticizer from a draughty conduit line cannot be too serious if a reasonable plasticizer is employed in the compound. A good rubber cable should have a high insulation resistance; this is intrinsic in the quality. It is certain, however, that such insulation values are unnecessary, and that p.v.c. can give satisfactory service. Neoprene is undoubtedly a first-class material for certain types of cable. The cost must, however, be taken into account.

We would point out to Mr. Raphael that the paper does not infer that p.v.c. cables are experimental, but it does infer, and correctly so, that the technique of using plastic cables is in the development stage. We agree that G.D.E.S.18 or an equivalent specification must be expanded eventually to cover compounds designed for use on cables for building work.

The American cables for 90–100° C, referred to by Mr. McKenzie, are of special construction and are limited in application. The term "tropical use" is an unfortunate one, for much depends on the local conditions and the working conditions.

We can foresee the use of many types of p.v.c. cables in the tropics, as well as cases in which they would be unsuitable.

It is known that the insulation resistance of p.v.c. can be raised by, say, 10^3 above the British maximum standard when circumstances permit. Otherwise we cannot see much hope of improvement electrically.

It is agreed that the final tests should be on the cable itself. It is, however, impossible to make a good cable with a bad compound, so that G.D.E.S.18 is a necessary step in procedure. Cable processing, as already mentioned, can produce defects even if a good compound is applied.

A full account of tear resistance of p.v.c. sheaths has not yet been published. It may be that p.v.c. has been somewhat misjudged in this respect.

We agree that the early development difficulties were considerable and that war-emergency conditions aggravated these. This may prove to have been a blessing in disguise, in that all technical points have been investigated more rigorously than might have been the case.

In reply to Mr. McNeill, we feel that 1002 compound will behave well under adverse conditions, provided that the conditions are suitable for p.v.c. His rapid alternations require definition, but for aircraft and ships we anticipate no pronounced effect on flexibility. We agree with his remarks on contraction, but feel that his experience with blue compound must be due to factors other than the pigment used. The use of p.v.c. cables in outdoor conduits exposed to the sun is purely a question of keeping within the specified temperatures.

Mr. Hutchings introduces the question of thermal resistivity. There appears to be some dispute about the actual value or range of values. Deductions from cable tests bring in other factors; this question of the rating of p.v.c. cables requires urgent attention. We tentatively suggest that the maximum conductor temperature of p.v.c. cables may have to be recalculated and revised upwards if Mr. Hutchings's values are approximately correct. We do not imagine that painting of p.v.c. cables will affect their volume resistivity in the same way as uniformly distributed pigment. Abrasion tests on plastics differ from normal abrasion tests because of the effect of heat generation on the plastic.

We suggest to Mr. Follett that it is necessary to consider every type of construction and every method of manufacture. The discussion shows clearly that the braided type may have a considerable field of use, despite the relative cheapness and simplicity of the unbraided type. The calculations leading to 57° C maximum working temperature for cables conforming with B.S.7 and the I.E.E. Wiring Regulations, are somewhat complicated. All the factors have been taken into account. The value is not ambient, but includes allowances for current loading. It corresponds to the American 60° C rating. For shorter life, temperatures up to 70° C are permissible, but it is desirable that the working conditions of each type of cable rated at 70° C should be carefully examined, and the construction of cable and type of compound incorporated in the design carefully considered. Further remarks on this point are given below in the reply to Mr. Bacon.

Work on polythene, polyisobutylene, etc., continues, but under war-emergency conditions technical effort has to follow the supply situation and the allocation of that supply to various cable usages.

Mr. Jessel's points have been dealt with in the replies to other speakers.

Mr. Bacon raises a point which has been largely dealt with above, but which can with advantage be further considered. Loss of plasticizer does cause shrinkage, but this is transverse shrinkage and should not cause trouble if confined to a few inches adjacent to the lampholder, particularly if there is no deforming pressure in this region. Longitudinal splitting of the insulation is due to manufacturing technique, and can and will be eliminated. War-emergency conditions have rendered this elimination a somewhat slow process. For this reason the cable industry has proceeded cautiously with regard to high-power-lamp connections, particularly since the temperatures attained are not always so clearly defined as in Mr. Bacon's case. It is now certain that p.v.c. is at least not inferior to normal rubber. As noted above, a p.v.c. cable exposed to 70° C continuously should shrink transversely at a comparatively low rate. There should be no longitudinal shrinkage and splitting. Braiding is a form of insurance against undue deterioration, particularly if deforming pressure is present.

We suggest to Mr. Meyer that the evolution of standardized grades of p.v.c. compound must of necessity be a gradual process; this evolution is by no means complete. Every precaution has, however, been taken to avoid sudden breaks in the continuity of evolution so that users are not unduly incommoded. It is always possible to produce non-concentric insulation by extrusion, whatever the material; p.v.c. can undoubtedly be used in thin walls much more easily than the majority of extrudable materials.

The discussion shows that there are diverse views among users with regard to the advantages of p.v.c. cables, and that only now, after considerable technical effort, justified by the war emergency, has the position been sufficiently stabilized to permit the protagonists to reply adequately to criticisms. We thank Dr. Miller for his contribution on nylon which we agree adds to the value of the paper. We did not intend to "damn with faint praise," but had to strike a middle course between omitting reference or exceeding our space allocation. The enamelled-wire field appeared to be worthy of separate treatment. Nylon has been proposed, however, as a protective covering for thermoplastics used as cable insulants. We admit Dr. Rosen's claim for the pioneer status of gutta-percha. In cases in which dielectric materials are associated with plasticizers or solvents in the course of manufacture, anomalous results occur. Also, as Dr. Miller points out, there are a variety of products covered by the name "nylon."

It is obvious that a paper of this nature could be expanded usefully to deal with many aspects of thermoplastic insulation, but we have not been able to touch on these.

THE MECHANISM OF THE CONTAMINATION OF PORCELAIN INSULATORS*

By W. G. THOMPSON, Ph.D., B.Sc., Member.†

(*The paper was first received 13th March, and in revised form 22nd November*, 1943.)

SUMMARY

An analysis of the nature of the air-borne particles which constitute the main source of contamination on outdoor porcelain insulators, and of the forces acting upon them in the electrostatic field around an insulator, suggests that these forces are inadequate to account completely for the observed distribution and the quantity of the deposits on insulator surfaces. Direct measurements of the field strengths close to the insulator confirm that the voltage gradients do not reach very high values under normal conditions, and that the electrical forces are proportionately weak. Investigations of the air flow over the insulators, and comparisons of the formations of air eddies observed in the flow over the geometrical forms associated with the complex shapes of insulators, show that the aerodynamic conditions have a considerable bearing upon the patterns formed by the deposits on the insulators. Wind-tunnel experiments provide results which illustrate the influence of the Reynolds' number, the applied voltage, the surface roughness, the wind velocity and the humidity, upon the distribution and amount of deposited matter. Moisture films constitute a special case of temporary contamination with sparking following the receding edges of the drying films. Finally, a method is suggested of estimating the flashover values of insulators from a consideration of the distribution of surface resistance as modified by the presence of deposited matter.

(1) INTRODUCTION

The distinctive patterns formed by the dirt deposits on transmission-line insulators which have been in service in polluted atmosphere suggest that the process of contamination is governed by definite physical laws. If this is so, then the nature of such laws should be evident from the behaviour of the air-borne contaminating particles as they come within the field of the insulator, and also from their reaction to the physical conditions at the surface of the insulator. It was decided to study the contamination of insulators from a somewhat academic viewpoint, and some formal experiments were conducted in the laboratory to determine the contribution of the various factors in the process of dirt deposition. The limitations of some of these tests are frankly admitted and the results are offered more from the scientific aspect rather than as criteria of those insulator designs which were of necessity subjected to accelerated pollution tests.

(2) THE NATURE OF THE PARTICLES AND THE FORCES ACTING UPON THEM

Impurities suspended in the atmosphere can be classified in two groups, (*a*) permanent and (*b*) temporary suspensions. The first group comprises the insoluble and non-condensable inorganic matter of ultra-microscopic size, which is maintained in suspension by the kinetic forces of the moving gas molecules and can be precipitated only by electrical means. The temporary suspensions include (*a*) the heavy inorganic particles which ultimately deposit by gravitation, (*b*) the organic material which either deposits or decomposes, and (*c*) water-vapour particles which either condense or disperse according to the temperature and wind conditions.

From data published annually by the Department of Scientific and Industrial Research and independent investigators[1] it is evident that the sizes of the particles suspended in the atmosphere vary considerably. Some data relating to the typical groups are given in Table 1.

Table 1

Nature of suspended matter		Diameter, microns
Inorganic	Smokes ..	0·001– 0·3
	Fumes ..	0·01 – 1·0
	Dust ..	1·0 – 100·0
Organic	Bacteria ..	1·0 – 10·0
	Plant spores ..	10·0 – 20·0
	Pollens ..	15·0 – 50·0
Water	Fog	1·0 – 50·0
	Mist	50·0 – 100·0
	Drizzle ..	100·0 – 400·0
	Rain	400·0 – 4 000·0

There is also a wide variation in the number of particles present in the air: these amount to some 200/cm^3 in fine weather and as many as 53 000/cm^3 in dense fog. In the latter case particles with diameters ranging from 1·5 microns downwards have been observed. It may be of interest to note that the size of particles used in the experiments described in this paper ranges from about 1 mm diameter for the turpentine smokes down to 0·3 micron for the fine tobacco smoke used to indicate air flow.

The forces acting upon the air-borne particles are of several kinds, kinetic, gravitational, electrical and aerodynamic. The kinetic forces resulting from the molecular collisions with the smallest particles have already been mentioned; they are responsible for the Brownian movement and the maintained suspension of the permanent impurities. The gravitational forces determine the rate of settling of the larger particles and the formation of deposits on the upper surfaces of insulators. For dust particles the mean rate of settling in still air is about 6 to 12 inches per hour, and unless the electrical forces are considerably stronger than gravity it is apparent even at this stage that high particle velocities are unlikely to be encountered.

Two kinds of electrical forces are operative with particles suspended in an electrostatic field. The first is exclusive to charged particles, the second to non-uniform fields. The charged particles involved in the present study are mainly the atmospheric ions; the more important facts concerning these have been summarized by Schonland.[2] Particularly relevant items are first the preponderance of large slowly-moving ions of the condensation nuclei or dust particle kinds, whose mobilities range from 0·0005 to 0·0003 cm/s/V/cm, and secondly that the great majority of ions carry a single elementary charge, either positive or negative. The particles will tend to move in the electrostatic field along the lines of force towards the positive or negative pole, according to the sign of the charge. The magnitude of the force P_c is a product of the field strength $\mathscr{E}$ in electrostatic units and the number of elemental charges on the particle ($n \times 4{\cdot}774$) in accordance with Coulomb's law. The electrostatic field of an insulator, however, alternates with the frequency of the power supply, and will cause an oscillatory motion of any charged particles. If for the moment the possible influence of corona effects be ignored, the

* Transmission Section paper.
† General Electric Co., Ltd.

mean Coulombic force is zero when considered over a whole cycle, as shown by equation (1).

$$P_c = 4{\cdot}774\pi\frac{1}{2\pi}\int_0^{2\pi} \mathscr{E}_{max} \sin \omega t dt = 0 \quad . \quad . \quad . \quad (1)$$

All particles, whether charged or uncharged, whose dielectric constant differs from that of air produce a distortion of the electrostatic field at their surfaces. In a uniform field the forces produced by the distortion are balanced; uncharged spherical particles will remain at rest and, although elongated particles may experience a turning moment, there will be no translatory forces. If the field is non-uniform, the forces are unbalanced and the particles tend to be drawn into the strongest part of the field. It is shown in textbooks on electrical theory[3] that the force is proportional to the volume of the particle and to the gradient of the square of the field strength, and is also a function of the dielectric constant. The equation for the force on a spherical particle of radius a and dielectric constant κ in an alternating field of force is shown in equation (2).

$$P_g = \frac{a^3}{2}\cdot\frac{\kappa-1}{\kappa+2}\cdot\frac{1}{2\pi}\int_0^{2\pi} \text{grad}\, \mathscr{E}^2_{max} \sin^2 \omega t dt$$

$$= \frac{a^3}{2}\cdot\frac{\kappa-1}{\kappa+2}\,\text{grad}\,\mathscr{E}^2_{r.m.s.} \quad . \quad . \quad (2)$$

and is not zero when integrated over the whole cycle.

These equations can be applied to the present problem in the same way as their unidirectional counterparts have been used in the study of electrostatic precipitators.[4] Numerous researches have also been made into the motion of fine particles suspended in air and into the movement of charged particles in a uniform direct-voltage field:[5] the forces acting on all particles in the direction of the field gradient have been discussed by Röth,[6] who has studied the deposition of dust on insulators subjected to the comparatively still air in a room.

To revert to the equation of the gradient force, the influence of the dielectric constant of the particle is indicated by the term $(\kappa - 1)/(\kappa + 2)$: this can be practically nil or unity according to whether the dielectric constant is unity or infinity. It follows that all air-borne particles will tend to be drawn into the field of the insulator, but the relative intensities of the forces involved for water vapour, soot and silica dust are 0·96, 0·6 and 0·45.

The determination of the term (grad $\mathscr{E}^2$) for each region of the complicated field-form of an insulator would be a lengthy process. A solution adopted by the author is to measure the actual field strength near the surface of the insulator with a given voltage applied, and to assume an approximate field-form from which the equivalent (grad $\mathscr{E}^2$) can be calculated. By way of illustration, if a coaxial arrangement be adopted for the equivalent field of a pin-type insulator, the field strength $\mathscr{E}^2$ at a radial distance x with a potential V applied to the insulator is given by equation (3), and grad $\mathscr{E}^2$ by equation (4).

$$\mathscr{E} = \frac{V}{x \log R/r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and

$$\text{grad}\,\mathscr{E}^2 = -\frac{2}{x^3}\left(\frac{V}{\log R/r}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Thus, if $\mathscr{E}$, V and x be measured directly the value of $\log R/r$ can be deduced, R and r being the corresponding hypothetical radii of the equivalent electrode arrangement. Once determined, this quantity is a numerical constant for a given insulator under stable conditions, and can therefore be used as a coefficient of the applied voltage in equation (4), so that by substituting the value of grad $\mathscr{E}^2$ in equation (2) the pull on a particle at a known distance from the insulator can be calculated. To quote an actual case, the insulator No. 1 shown in Fig. 1 with 20 kV applied had a measured field strength of 0·8 kV/cm at a radial distance of 6 cm from the axis, giving an equivalent grad $\mathscr{E}^2$ of $0{\cdot}1152\, V^2/x^3$.

The natural rate of settling of particles in air depends upon their weight, and a comparison with the pull on the particles due to the insulator field is of interest. With V measured in kilovolts the force/weight ratio is given by equation (5).

$$\frac{P_g}{w} = \frac{11\dfrac{\kappa-1}{\kappa+2}\left(\dfrac{V}{\log R/r}\right)^2\dfrac{1}{x^3}}{\dfrac{4}{3}\pi\delta \cdot 981} \quad . \quad . \quad . \quad . \quad (5)$$

Substitution of the values corresponding to the particular example quoted above, shows that the force/weight ratio for water particles at the insulator surface is only 0·0005. The ratio indicates that the effect of the insulator field at ordinary working voltages is negligibly small. It is evident that this must be so, otherwise insulators would become completely coated in an intolerably short time.

(2.1) Air Resistance

The above result also suggests that the air motion need not be large to overcome the electrostatic attraction. The motion of very small particles is best calculated from Stokes's law as indicated by

$$v = \frac{P}{6\pi\eta a} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where v is the velocity, P the driving force, η the internal friction

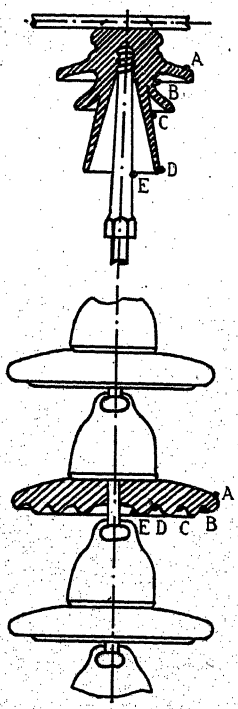


Fig. 1.—Observed field strengths at insulator surfaces.

20 kV applied		Measured field strength (kV/cm) at				
Type	State	A	B	C	D	E
Pin (a) (Fig. 10)	Dry	1·25	1·36	1·62	0·54	0·92
	Fog	1·67	0·27	0·81	1·08	0·32
	Rain	1·0	0·27	0·22	0·54	0·22
Pin (b) (Fig. 10)	Dry	0·9	1·04	0·63	0·21	1·0
Disc	Dry	0·2	0·25	0·45	0·9	1·7
	Fog	0·3	1·2	1·5	1·3	1·7
	Rain	0·35	0·9	1·4	1·4	2·5

of the gas ($\eta = 1{\cdot}8 \times 10$ c.g.s.), and a the radius of the particle. For field strengths of a few kV per cm the above equation gives velocities of the order of 10^{-3} cm/sec or less, a result in general agreement with the investigations of Ladenburg, who also found the gradient forces inadequate to account for the operation of electrostatic precipitators. As a matter of passing interest, the air resistance of larger particles, including raindrops, can be deduced from the experimental data determined by Lunnon,[7] who found that the resistance to the motion of falling spheres in air is given by an equation of the type

$$S = \phi h v^2 d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where d is the diameter of the sphere, v the velocity, h the air density and ϕ a coefficient which ranges from 0·132 to 0·168. With a mean value of $\phi = 0{\cdot}15$, h and d 0·00125 and 1 mm respectively, $S = 0{\cdot}1875\, v^2$. Immediately any relative motion is produced with respect to the air, the particle will experience a drag proportional to the square of the velocity. This factor will determine the limiting velocity for a given field gradient and also whether the particle is finally captured by the field of the insulator or whether it is swept away by the wind. So far as can be ascertained, however, the particle velocities for field strengths below the corona limit are so low that only on the calmest days can the gradient field have any serious influence upon the motion of the particle.

(2.2) Corona Discharge

The essential part played by corona discharge in the process of dust precipitation is well known; in fact the electric wind from the discharge points has been shown to be the dominating factor in the operation of precipitators. In place of the high direct voltage with a negative electrode as the source of discharge, the transmission-line insulator has an alternating voltage impressed with alternate half-cycles of positive and negative corona. The rectifying effect of the diverging field is sufficient to impart a unidirectional character to the motion of the particles under corona conditions. With corona, ionization will be increased considerably beyond the normal atmospheric conditions, both as regards the number of ions present and the number of elemental charges on each particle, and Seeliger[4] quotes the case of particles with 1 000 elemental charges. The induced motion of a charged particle in a strong alternating field is in the form of small elongated loops, and a typical motion of this kind has been observed with ammonium chloride smoke in a flask fitted with electrodes energized by an alternating voltage.[8]

Although the corona discharge may be intense under adverse climatic conditions, it is confined to the most highly-stressed parts of the insulator. The electric wind, in the form of air jets directed away from the discharge points, induces local air circulations which promote the flow of charged and uncharged particles over the surface of the insulator. Measurements made by the author indicated that the velocity of the air stream is proportional to the applied voltage,[8] while in addition the electric charge associated with the wind is found to be negative at a distance from the source, so that charged particles would also experience a unidirectional force. In view of the air resistance, however, it is doubtful whether they could have any appreciable movement against the air stream. The corona discharge from the metal fittings or condensation droplets on an insulator is most pronounced in fog and rain, and the water particles tend to coalesce in the electrostatic field and are directed against the various parts of the insulator surface by the electric wind. At the surface any dust particles carried by the electric wind will be retained by the surface tension of the moisture film. Thus, in effect, corona associated with the large number of particles present in fog, and the receptive state of the insulator surfaces, constitute important factors in the mechanism of contamination.

(3) THE ELECTRIC FIELD OF AN INSULATOR

The forms of the electrostatic fields of the different types of insulator are well known as they have been determined both experimentally and graphically by several investigators.[9] The direction of the lines of force can be explored by means of a straw needle, and the intensity deduced from the potential distribution at the insulator surface. An alternative method adopted by the author was to measure the field strength directly by observing the oscillations of a small brass ellipsoid suspended by an unspun silk thread in the various parts of the field around the insulator. The ellipsoid had previously been calibrated and the field strength was determined from the equation

$$\mathscr{E} = K(n_1 - n_0)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

K being the constant of the ellipsoid, n_1 the number of swings per second with the field applied and n_0 the number of free swings per second.[10]

In order to obtain some idea of the field strengths prevailing in practice, field strengths of some insulators were measured at their rated working voltages, and in the corresponding dry, rain and fog states. The results are shown in Fig. 1. The fog state was imitated by subjecting the cold insulator to a steam bath, so that condensation took place on all surfaces and provided the appropriate distortion of the insulator field. Such procedure is admittedly open to criticism inasmuch as a low temperature is usually associated with fog, but the method used has been shown to give results comparable with actual conditions.[11]

The salient features of the field forms of insulators, such as the stress concentration round the shackle in the suspension type, the axial distribution around the spindle in the pin-type, and the formation of equipotential surfaces in the design of the porcelain shape, have often been discussed. The direct determination of the field strength by the method of timed oscillations takes into account the non-uniformities due to these various features. A striking demonstration of the validity of the method is provided by the accurate measurements obtained in the investigation of the field strength of the non-uniform field of an air condenser. Some details of the ellipsoid and the results of this test are given in Appendix 11.1.

So far as can be gathered from the foregoing tests and from the published observations of other workers, there is no reason to believe that insulator field strengths reach abnormally high values under ordinary conditions. The stress in the air around the shackle on the line side of a 132-kV insulator string approaches the corona limit, while in the pin-type the values are considerably less. The calculations and the experimental evidence tend to show that in fine weather the electrical forces are comparatively weak; it is only during rain or fog when electrical discharges are present that the electric field of the insulator plays a direct part in bringing the contaminating particles to the insulator surface.

(4) THE AIR FLOW AROUND AN INSULATOR

Except on the very calmest of days an outdoor insulator will always be subjected to a moving air stream, and will thus exhibit the turbulence and wake effects exhibited by all aerodynamic bodies. These effects have their origin in the velocity gradient at the surface of the body. At very low air speeds the flow follows approximately the contours of any obstacle in the air stream and the flow is described as laminar, or streamlined. At higher air speeds, the velocity gradient at the surface is sufficiently large to cause a breakdown of the streamline flow and a breaking away of the Prandtl boundary layer in the form of sheets of small

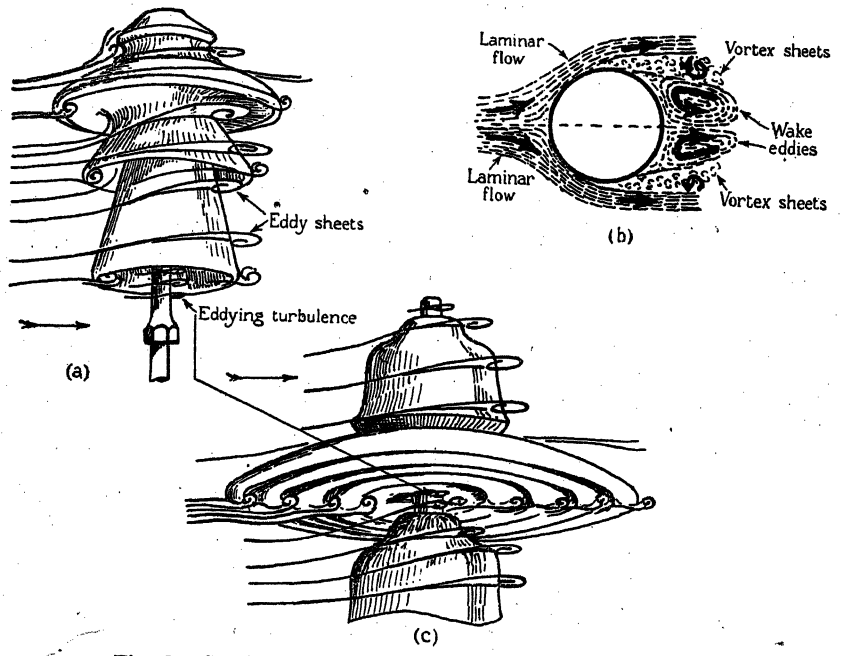


Fig. 2.—Smoke traces of eddy formations around insulators.
(*a*) Pin type. (*b*) Typical air-flow around cylinder.
(*c*) Air flow over suspension-type insulator.

vortices on either side of the body. This occurs at definite values of the Reynolds' number, and large slowly-moving eddies are formed in the region between the vortex sheets, i.e. directly in the wake of the body. An insulator will thus be subjected to three types of air flow, as shown in Fig. 2; the laminar flow on the windward wide, the high-speed eddies in the vortex sheets on either side, and the slowly-moving eddies in the wake. It will be shown later that each of these types of flow makes a characteristic contribution to the deposition of foreign matter on the surface of the insulator. In addition to these effects the deflecting action of the insulator sheds must also be considered, and the combined phenomena can be conveniently demonstrated at low air speeds by means of smoke traces. Fig. 2 also shows the smoke patterns for two typical forms of insulator. These patterns were drawn diagrammatically from the direct observation of the air movement over the insulator, as indicated by the smoke from a smouldering taper held at various points near the insulator. The different types of insulator can be resolved into a number of standard geometrical forms whose air-flow characteristics have already been exhaustively studied and to which reference will be found in any book on advanced aerodynamics. Particularly relevant forms are the cylinder, the hollow cylinder, the truncated cone, and the open-ended pipe with an axial spindle. Fig. 3 gives a pictorial illustration of the types of air circulation associated with some of these forms, and sufficient knowledge is available to determine the air flow over similarly-shaped parts of insulators.

To quote an example of the foregoing possibility, Fage[12] has determined experimentally the separation of the vortex sheets from the sides of a cylinder; he found that this occurred at angles between 86° and 105° to the axis of flow, with the centre line of the cylinder as the origin. The air speeds ranged from 22·0 to 71·4 ft/sec and corresponded to a change in the Reynolds' number from 102 600 to 333 000. It follows that in practice the air-flow pattern around an insulator will alter both with the wind speed and the dimensions of the body. The former, taken at an average value of 25 m.p.h. and increased to a maximum of 50 m.p.h., would be equivalent to a change of the Reynolds' number in the ratio of 1 : 2. A similar variation arises as a result of the shapes of the component parts of the insulator and its fittings; thus for a given wind speed over an 8-in diameter insulator the Reynolds' number can range from 70 000 to 250 000 at positions corresponding to the different diameters of the sheds.

In order to study the influence of the three types of air flow on the deposition of dirt at the insulator surface, a closed-circuit wind tunnel was built, complete with the usual baffles and honeycombs for air control, and fitted with means for injecting smoke, cement dust and steam into the flow. Some data about the tunnel are given in Appendix 11.2. Various standard forms were subjected to test, as well as insulators with their working voltage applied, while the tunnel was also calibrated in terms of fan speed and the weight and size of suspended matter per cm^3. The experimental results obtained were in accordance with air-flow theory. On smooth surfaces the flow was uninterrupted and the particles moved relatively fast, so that they were less likely to be retained by the electrostatic field. In addition the surface was subjected to a scouring action so that any particles which attempted to adhere were removed. On certain parts of the insulator, particles tended to be thrown directly on to the surface, and this gave rise to a thick, coagulated form of deposit. At other points where the air flow broke into eddies the particles took a longer time to traverse the field of the insulator and tended to be thrown against the surface by the centrifugal force. This gave rise to a more uniform and finely-divided form of deposit. Fig. 4 shows the results obtained with a smooth cylindrical surface, and for the purposes of explanation the cylinder can be divided into three regions according to the distribution of flow. They are: the area of direct impact, the region of tangential flow, and the wake area. The deposits from each region were carefully removed in sections and weighed; the results are plotted in Fig. 4. It was found that a deposit of uniformly varying thickness occurs in the front, the thickness being proportional to the angle of impact. There was no deposit in the

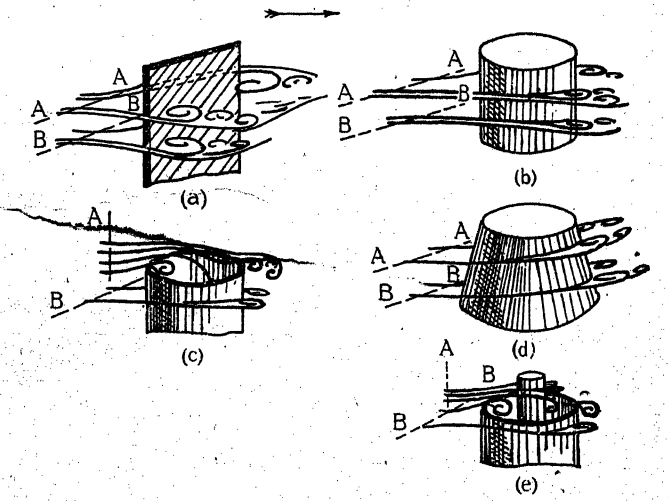


Fig. 3.—Air-flow over geometrical shapes.
(*a*) Plane. (*b*) Cylinder.
(*c*) Hollow pipe. (*d*) Truncated core.
(*e*) Coaxial cylinders.

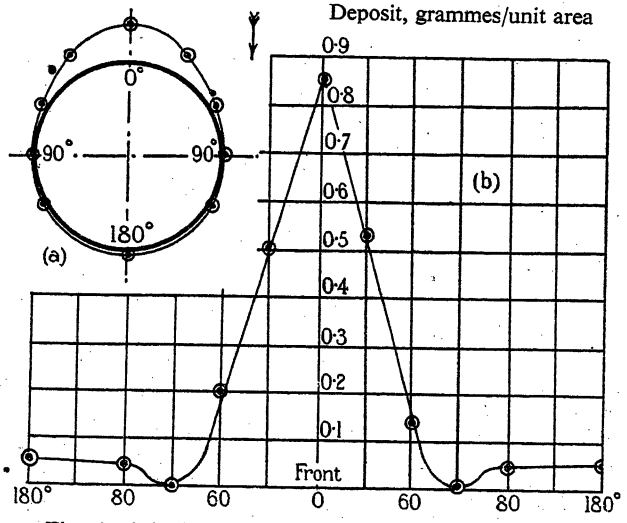


Fig. 4.—Distribution of deposit on a cylindrical surface.
(*a*) Plan with radial scale enlarged.
(*b*) Developed distribution.

tangential region where the impact angle is zero, and a deposit of uniform thickness was formed on the rear half of the cylinder in the region of the wake. Horizontal surfaces placed in the air stream beside the cylinder showed traces of the vortex sheets and the eddy formation in the wake of the cylinder.

A second interesting example tested in the wind tunnel was the truncated cone shown in Fig. 5. Here the pattern of the deposit was not parallel to the axis of the cone, but displaced according to the Reynolds' number corresponding to the changing diameter of the horizontal sections in a manner which is in agreement with the air-flow researches of Fage. That is to say, the smaller the radial dimension the earlier the transition from the region of direct impact to that of the wake effect. The contamination thus showed a clean oblique strip down the cone, and the boundaries of this strip approximated to the results of Fage's tests, also tabulated in Fig. 5.

To anticipate some later results, the types of insulator examined under these conditions all exhibited the same features, and the distribution of deposited matter can be summarized as follows: On the conical vertical surfaces the deposit is of variable thickness on the windward side, changing to a uniform thickness on the lee side, at an angular position which, regarded in plan, depends upon the Reynolds' number. Horizontal or nearly horizontal surfaces under the sheds exhibit deposit patterns in conformity with the air flow in the wake of neighbouring vertical surfaces. Ribs arranged concentrically, as on disc-type suspension insulators, show deposits on the windward edges, but are comparatively clear where their curvature is in the direction of flow. Deeper concentric arrangements exhibit the same tendency around the edges, but inside show a fairly uniform deposit which diminishes as the distance from the open end increases.

(5) THE COMBINED ACTION OF THE ELECTRIC FIELD AND AIR FLOW

In practice neither the electric field nor the air flow is constant so that experimental conditions can represent only a particular phase of the general problem. The electric field changes with the moisture distribution and with the different types of insulator, while the air flow may vary from practically laminar flow in still air to turbulence in high wind. Moreover, the distribution of the turbulence will undergo a polar rotation with respect to the

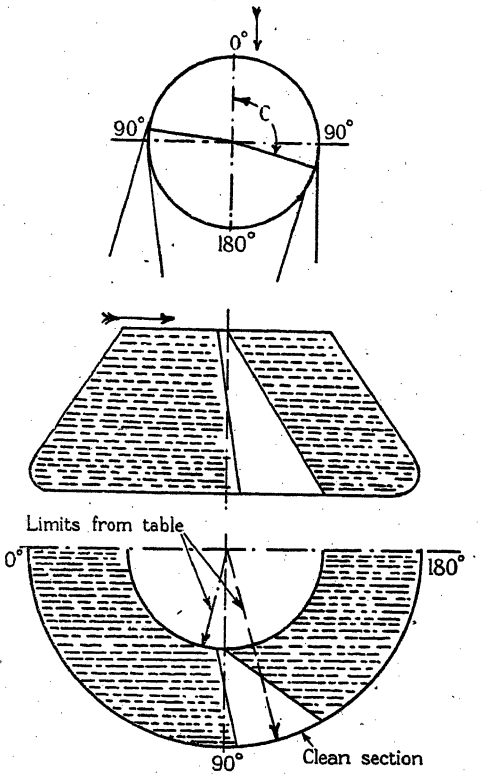


Fig. 5.—Distribution of deposit on a conical surface.

v (ft/sec)	22·0	26·9	39·2	57·9	71·4
$vl/\nu \times 10^3$	102·6	125·4	182·8	270·0	330·0
C (deg)	86	92	94	105	105

v = air velocity.
l = cylinder diameter.
ν = kinematic viscosity.
vl/ν = Reynolds' number.
C = angular position of start of turbulence.

insulator, according to the direction of the wind. The implications of Sections 3 and 4 are that the electrostatic field is restricted in its attracting action to those regions where the air flow is low, or where eddying causes the particle to be retained in the strong part of the field for an appreciable time. The following experimental evidence, however, shows that this should not be taken to exclude the fact that the electrostatic effects play a vital part in the retention of those particles which actually come into contact with the surface of the insulator.

(5.1) Surface Effects

The factors involved in the final retention of the particles at the insulator surface are the boundary layer of still air at the surface, the surface roughness, the applied voltage, and the humidity. The experimental investigation of each of these items was carried out in the wind tunnel. A cylindrical test-piece with an internal electrode was used, so that a sensibly radial field was produced. The soot deposit upon the test piece was collected after each test, which occupied about half an hour. The influence of the wind velocity on the surface deposit was tested by circulating the air in the wind tunnel at successively increasing air speeds, and weighing the amount deposited on the cylindrical surface in equal intervals of time. In this test and in the other tests which are about to be described, the quantitative results obtained are relative to each group only, that is to say the values

for each experiment can be compared only with other experiments in the same set. Because of the complexity of the variables involved no attempt was made to correlate the amount deposited per unit area with the quantity circulated during the total time of each test.

The results of the wind-velocity test showed that in three tests out of the four the weight of deposited matter was almost exactly the same (see Table 2), but the size of the aggregates deposited at high velocity was very much greater than at the lowest air speed.

Table 2

VARIATION OF DEPOSIT WITH WIND VELOCITY. DURATION OF TEST, 30 MINUTES

Air speed	Deposit
ft/min	g
132	0·0027 (fine film)
265	0·0029
397	0·0018
660	0·0028 (flakes)

In the above test the same total quantity of suspended matter was present in the air in each case, but at the higher speeds the same quantity was passed over the insulator a proportionately greater number of times. The fact that this merely resulted in the same amount being deposited by the end of each test suggests that the matter deposited may vary in proportion to the quantity of contaminating matter passing over the insulator in a given interval of time, but inversely in proportion to the air velocity.

To ascertain the influence of the surface roughness upon the rate of deposition, measurements were made with glass-paper surfaces whose successive degrees of roughness were determined with the aid of a microscope. The paper was cut into strips and mounted on the surface of the porcelain. The results are given in Fig. 6 and indicate that the amount deposited is directly pro-

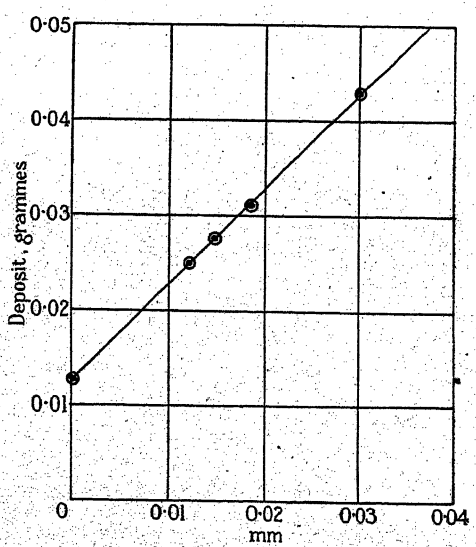


Fig. 6.—Influence of surface irregularity on weight of deposited matter.

portional to the height of the surface irregularity. Smooth porcelain corresponds to the zero value, while the constant represented by the intercept in Fig. 6 depends upon the adhesive properties of the contaminating matter. A practical conclusion from this experiment is that the deposit will concentrate in ever-increasing quantities on those parts of an insulator which are prone to contamination. Incidentally, calculations show that on the basis of the amount of suspended matter in the air the depth of the air layer disturbed at the rough surface is about twice that of the surface variation.

To determine the influence of the applied voltage, successively increasing voltages were applied to the electrode inside the porcelain for each half-hour test. The results are shown in Fig. 7,

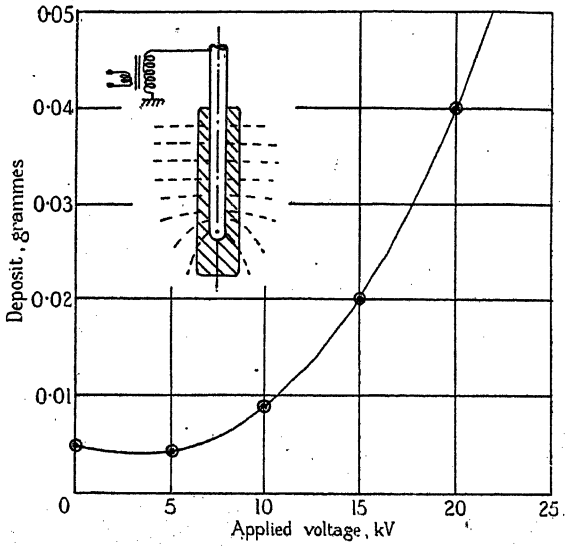


Fig. 7.—Influence of applied voltage on weight of deposited matter.

and it will be observed that although the distribution of dirt was similar to that in Fig. 4, the weight of matter retained on the surface of the insulator was exactly proportional to the square of the applied voltage, a result in agreement with electrostatic theory but controlled by air-flow conditions.

Next, the influence of the relative humidity was studied, but with a totally different kind of result. The humidity during the tests was measured by the wet- and dry-bulb thermometer method, which gave very consistent results in the wind tunnel provided the wet bulb was free from deposit. Table 3 shows the final results of the experiment, and it will be seen that the humidity itself had very little influence upon the amount deposited; a far more important factor was the state of the porcelain surface—the deposit increased tenfold as soon as the porcelain was wetted.

Table 3

VARIATION OF DEPOSIT WITH HUMIDITY. DURATION OF TEST, 30 MINUTES

Average temperature		Humidity	Deposit
Dry bulb	Wet bulb		
°F	°F	%	g
73·0	71·5	97·0	0·0422*
65·0	61·0	90·0	0·0016
66·5	60·7	85·5	0·0004

* Surface wet.

Reference has already been made to the testing of different insulator forms in the wind tunnel, and Fig. 8 shows the typical patterns produced on the under-side of a pin-type and suspension-type insulator, respectively. The information obtained from

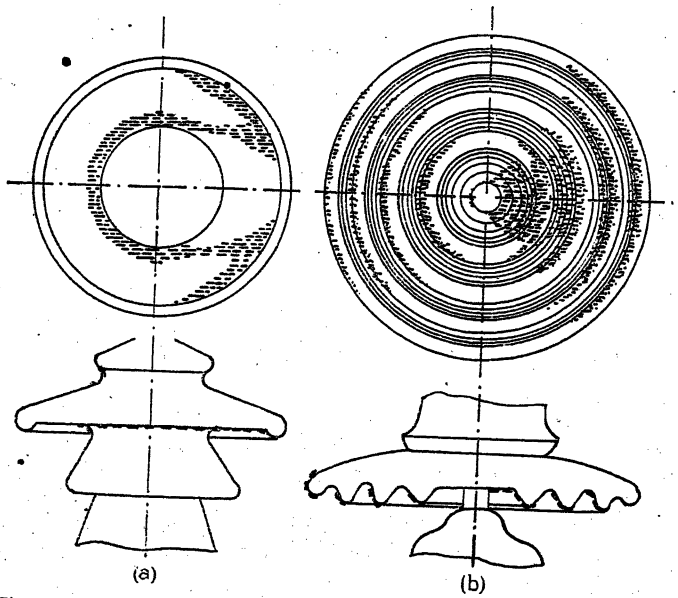
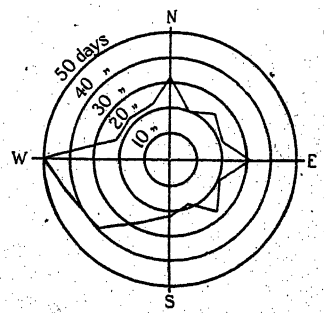


Fig. 8.—Observed distributions on under-sides of insulators exposed in wind tunnel.
(*a*) Pin type. (*b*) Suspension type.
Wind direction, left to right.

these wind-tunnel experiments suggests a line of approach to the problem of forecasting the probable performance of a given design of insulator, from the contamination standpoint. The dirt pattern produced in the wind tunnel represents the case of a constant wind direction. In practice, additional information about the position of the insulator in relation to probable sources of atmospheric contamination and the meteorological information about wind direction and the amount of rain and fog would be necessary. A convenient starting-point is the polar diagram of wind distribution, and Fig. 9 shows a typical diagram for the British Isles with the radial scale as the number of days on which the wind blows in a given direction. If the amount of contamination is constant, irrespective of the wind direction, e.g. near the middle of a large industrial area, a distribution corresponding to Fig. 9 will be produced on the underside of the insulator. This figure is deduced by superimposing the typical pattern from Fig. 8 on itself in the appropriate angular positions corresponding to the different wind directions. Where the source of contamination is localized, e.g. near an isolated factory or along one side of a railway line, a result similar to Fig. 8 will be obtained, the orientation depending upon the prevailing wind.



Polar diagram of wind direction for one year's data

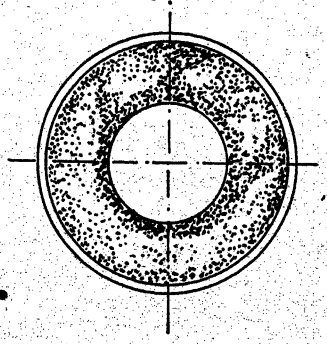


Fig. 9.—Computed distribution from wind data.

The foregoing argument applies to all parts of the insulator surface, so that it is possible to map out those areas which are likely to become heavily coated with dirt deposits and so obtain a picture of the probable condition of the insulator after a long period of service. In practice, the actual contamination can consist of widely different substances, such as soot, tar, salt spray, cement dust, bauxite, and organic matter. These will vary greatly in adhesive properties, hardness, and electrical conductivity; many forms are non-conducting when dry and conducting only when wet. Where salt is present, there is always the danger of deliquescence, although the atmosphere itself may not be saturated. It is clear that moisture films must therefore play an important part in determining the behaviour of the insulator in the contaminated state.

(6) MOISTURE FILMS

The principal phenomena accompanying moisture films on insulator surfaces are (*a*) the distortion of the electrostatic field, together with a change in the potential distribution, (*b*) the change in the surface resistance of coated portions and the bridging of these portions by conducting moisture paths, (*c*) the cycles of alternate heating and condensation caused by the drying-out and re-forming of moisture film over certain parts, accompanied by sparking following the receding sharp edges of the film. Tests made on a cylindrical porcelain surface which had been exposed to the weather for some weeks gave flashover values of 6·0 kV/cm when dry, and 2·8 kV/cm when wet, compared with 6·0 kV/cm and 3·0 kV/cm, respectively, when clean.

Moisture films can be divided into four groups, (*a*) the surface film which is present even in dry weather, (*b*) the film produced as a result of temperature differences between the insulator and the surrounding air, (*c*) the film which forms on the insulator in mist and fog, and (*d*) the surface wetting produced by drizzle and rain.

Films belonging to the first group give rise to no practical difficulty and are usually associated with the surface resistivities of solids. It is worth noting, however, that the leakage current shows a considerable variation with the relative humidity. Table 4 shows a typical record obtained with the disc-type

Table 4

Humidity	Leakage current	
	Dry	Light rain
%	μA	μA
98	175	350
95	148	248
90	125	160
85	110	115
80	100	Not raining
75	95	
50	87	
26	75	

insulator in Fig. 1; two of these insulators were suspended in series so that their leakage current could be measured with 20 kV applied.

The second type of moisture film is usually encountered on cold insulators whose thermal time-lag has maintained their temperature below that of the surrounding air, thereby causing the insulators to act as condensing surfaces. This effect is a well-known source of difficulty when switching-in a transmission line which has been out of service. The differential drying action of the wetted surface results in a change in the voltage distribution of the insulator and may cause abnormal voltage gradients. The unequal rates of drying can arise from such causes as the change in the cross-section of the leakage path on an insulator surface, the varying current density produced by capacitance current flowing to the moisture films, and differences due to an initially fortuitous distribution of the moisture on the surface. An indication of the mathematical treatment of this problem is given in Appendix 11.3. The chief interest, however, is the effect of the differential drying in amplifying the uneven distribution of potential on the surface of a contaminated insulator, the consequences of which are dealt with in Section 7.

The third process of moisture deposition is effected by the movement of suspended water-vapour particles of microscopic dimensions, which has already been discussed. Two other points may be mentioned, namely the tendency of these particles to coalesce under the influence of the electrostatic field, and the drying action as well as the particle-carrying effect of the corona wind. If the rate of deposition is sufficient to cause complete surface wetting, continuous sparking may take place locally on the insulator surface between the more heavily-wetted patches on adjacent parts.

The problem of rain-wetted surfaces has been thoroughly investigated by numerous research workers,[9, 13] and mention will be made only of the encrustations of deposited matter left by evaporation of rain drops at the edges of the insulator sheds. These encrustations build up to provide a local roughening of the surface, so that deposits accumulate at a progressively increasing rate. A similar effect takes place in a more distributed form on the upper sides of insulator sheds, with the result that although they are actually rain-washed they present a gradually-increasing filmed appearance. The build-up of this film is too slow to reproduce artificially, and it is surmised that the two main causes of its formation are the natural settling-out of solid matter from the atmosphere and the bringing-down of similar contamination by raindrops. In both cases the moisture finally evaporates from the surface of the insulator, leaving an extremely fine and tenacious film which can only be removed by proper cleaning.

(7) CONDUCTING DEPOSITS AND FLASHOVER

A clean insulator or insulator string will withstand many times its working voltage without flashing over, yet in practice insulator flashover is known to occur at voltages within the range of ordinary operating conditions. Failures in these circumstances indicate that a redistribution of potential must take place on the insulator surface to enable the arcing to start. With a very humid atmosphere some types of deposit become relatively good conductors, and this, in conjunction with the differential drying of the insulator, throws the whole strain of insulation upon the remaining clean parts of the surface. It is recognized that the measured total resistance of an insulator generally provides a very inadequate indication of the working condition. If, however, the problem is reduced to the study of the clean high-resistance paths connecting isolated conducting areas, the possibilities of a quantitative treatment are considerably improved, particularly as the different parts are maintained at potentials governed partly by their distributed capacitances, but much more so by the leakage current over the surface of the contaminated insulator.

In order to facilitate resistivity measurements, the group of insulators illustrated in Fig. 10 were all fitted with small conducting tabs at the numbered positions in the sectional view.

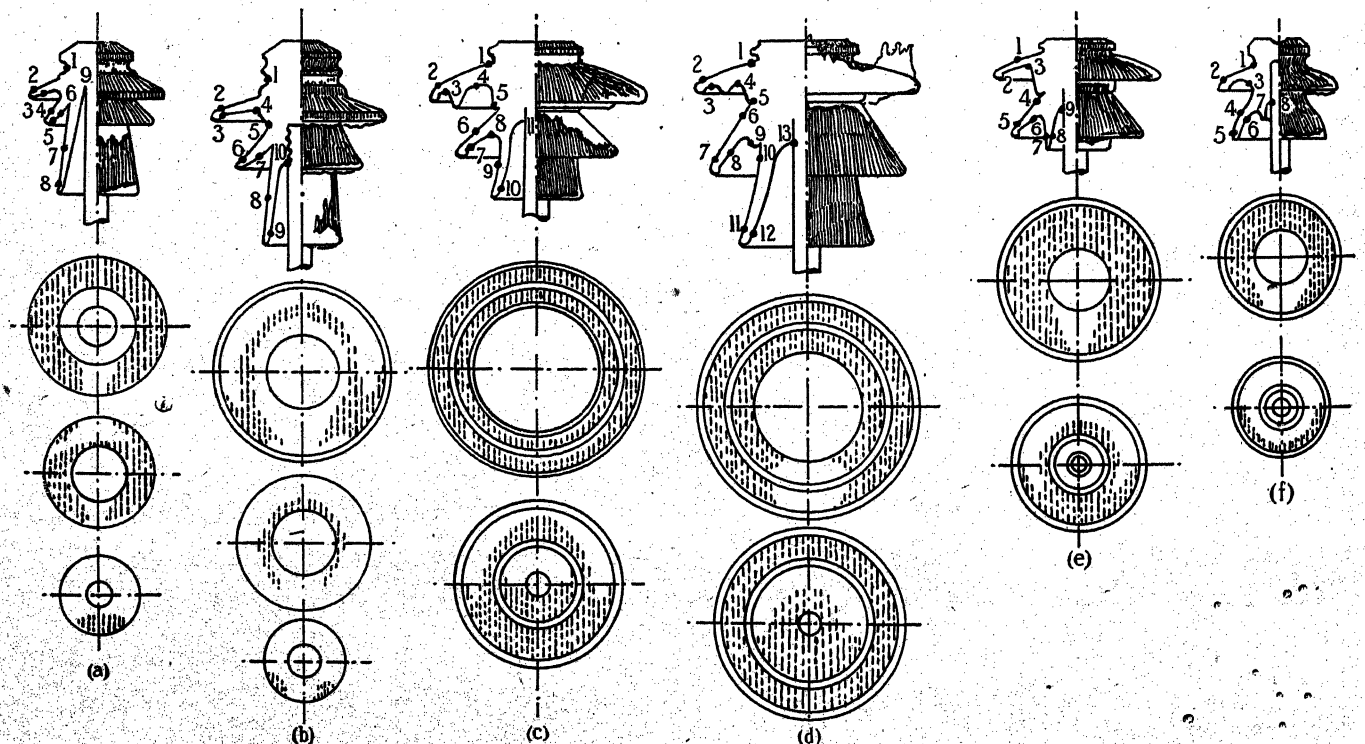


Fig. 10.—Measurement points and distribution of deposits on under-sides of tested insulators. Arcing at start of flashover shown on right of axis.

The insulators were then soiled in turn in the wind tunnel by exposing them with their working voltage applied for about 6 hours in some cases and about 12 hours with large units. These durations were determined from preliminary tests devised to ascertain the state at which the insulators would fail at about twice their working voltage, and it was found that contamination had to be extremely bad before this occurred. After soiling, each insulator was taken out and the resistance of the paths between consecutive conducting tabs was measured. The insulators were then tested for flashover under fog conditions at 50 c/s. As a result of their treatment the insulators exhibited the familiar patterns shown in Fig. 10, and the tests showed that the start of flashover was by pilot sparking across the clean parts of the surface, except where intense corona discharge occurred between thickly-coated, closely-spaced ribs.

It is convenient at this stage to mention that the testing transformer should have adequate power available to maintain a power arc, although its overload-relay settings may prevent the total destruction of the insulator, which could occur in practice. In some cases the more heavily-coated parts of the insulator may pass sufficient current to cause the transformer to be tripped out without arcing showing over the whole surface of the porcelain, and it is often difficult to differentiate between conduction and breakdown. The tests showed that this was not a vital issue in the present instance, as the power available ensured sufficient arc flame from the clean sections to complete the flashover of the insulator under test. Photographic records were taken of each insulator during the tests, and the position and appearances of the arc discharges are shown in Fig. 10.

The results obtained suggested that the flashover voltage of an insulator could be estimated from a knowledge of its surface conditions; a method of forecasting the distribution of the surface deposits has already been given. To reduce the complex three-dimensional case to an equivalent two-dimensional form, the developed surface area of the insulator can be drawn geometrically to scale and the contaminated parts plotted thereon, as shown in Fig. 11.

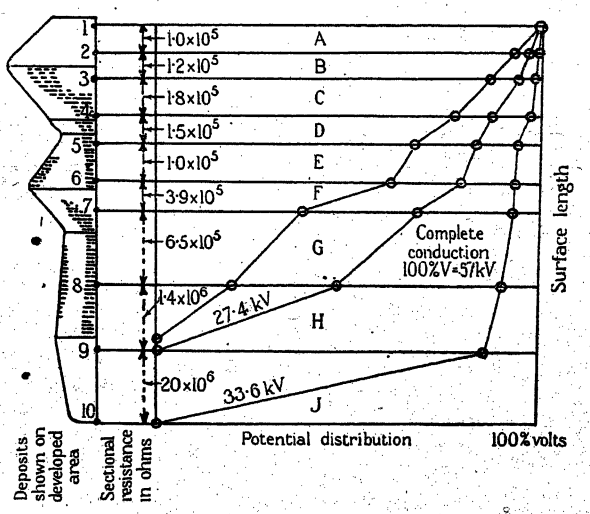


Fig. 11.—Determination of flashover voltage from surface-resistance measurements. Insulator (b) (Fig. 10). Estimated flashover voltage, 57 kV.

In the calculation of the flashover voltage, it will be presumed that the resistance distribution for the insulator surface has been determined either by direct measurement or by estimation from a developed area drawing showing the contamination. A voltage is assumed to be applied to the insulator and increased until the most highly-stressed section of the insulator has a voltage gradient of 3 kV/cm. This section is assumed to be clean and wet, and the voltage across it can be estimated by multiplying the length by the voltage gradient just quoted. The failure of this section may or may not lead to the complete failure of the insulator. This will be governed by the condition of the remainder of the insulator, and the total voltage across the insulator is found by taking the ratio of the total resistance to the section resistance and multiplying by the section voltage.

The first section is assumed to fail at 3 kV/cm. Its resistance is therefore deducted from the total resistance, and the voltage gradient across the next highest-stressed section calculated to see whether this exceeds 3 kV/cm. If it does so the total voltage is considered as being maintained, and this second section is regarded as having also flashed over. If the gradient is less than 3 kV/cm, then the voltage across the second section is calculated at 3 kV/cm and the new total voltage determined. The process is repeated until all the clean parts of the insulator have been accounted for. Attention is then directed to the lower-resistance sections. These are treated in a similar manner, but with the proviso that sections whose resistances are less than 1 megohm/cm but greater than 0·1 megohm/cm are considered to have a breakdown voltage of 2·8 kV/cm, corresponding to the dirty porcelain. Below 0·1 megohm/cm the insulation resistance is practically negligible for high-voltage purposes, and with these sections alone in circuit the flashover of the insulator is considered to be complete.

Table 5 gives the resistance measurements and calculated flashover voltages for the set of insulators in Fig. 10, indicating the main stages in the calculation for each insulator. The Table also shows a comparison between the estimated and actual flashover values and the agreement between the hypothetical and actual arcing surfaces after the accelerated contamination tests. It will be seen that the results agree remarkably closely, despite the various forms of insulator and the approximate nature of the assumptions involved. The discrepancy in the case of No. 6 was due to the intense corona discharge between the stem and the more thickly coated parts of the inner sheds.

(8) CONCLUSIONS

There is no doubt that, in the final determination of the performance of an insulator from the anti-dirt standpoint, it is essential to have recourse to the test racks of the testing stations and the manufacturers' laboratories, and to supplement the evidence obtained by service experience on overhead lines. It is admitted that the complete account must involve a study of the means by which material deposited on insulators is removed by wind, rain and frost, but there seems little object in attempting a study of this nature using only artificial deposits. The claim is made, however, that the present paper provides a reasonable working hypothesis of the mechanism of insulator contamination and may suggest possible lines of attack on the practical problems involved.

(9) ACKNOWLEDGMENTS

The author acknowledges his indebtedness to the late Prof. W. M. Thornton, O.B.E., D.Sc., and to the Department of Scientific and Industrial Research for facilities in connection with the experimental work on which this paper is based.

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Table 5

ESTIMATION OF FLASHOVER VOLTAGES OF THE INSULATORS SHOWN IN FIG. 10, BASED ON RESISTANCE MEASUREMENTS BETWEEN SELECTED POINTS ON THEIR SURFACES.

Insulator No. 1

Max. dia. 8·75 in
Creepage length 18·75 in
Total resistance 1 519·07 MΩ

Contact section Point	(Line)	Sect. res. MΩ	Sect. length cm	MΩ/cm
1				
2	A	0·04	4·25	0·009
3	B	0·03	3·3	0·009
4	C	3·0	6·5	0·46
5	D	10	3·54	2·75
6	E	500	3·0	166
7	F	1 000	6·6	152
8	G	1·5	6·0	0·25
9	H	4·5	15·8	0·285
10	J			
11	K			
12	L			
13	M			
		Earth		

Calculations

Sects. E and F have approximately equal gradients and will fail together.
At 3 kV/cm voltage across E = 9·0 kV
do. F = 19·8 kV
Total = 29·2 kV
Remaining resistance 1 519·17 − 1 500 = 19·07 MΩ.
Sect. D has now 6·5 kV/cm and will arc-over without increase of voltage.
Resistance of remaining sections is low, and as H is exposed to corona from spindle with 15 kV across, this section will also arc and insulator should flash over at about 30 kV.

Flashover voltage:	Estimated	30 kV
	Observed	35 kV
Arcing sections:	Estimated	E F D H
	Observed	A E F H

Insulator No. 2

Max. dia. 10 in
Creepage length 21·5 in
Total resistance 22·99 MΩ

Sect. res. MΩ	Sect. length cm	MΩ/cm
0·1	4·7	0·022
1·2	2·67	0·032
0·18	6·4	0·028
0·15	3·8	0·036
0·1	4·85	0·02
0·39	4·05	0·09
0·65	11·5	0·056
1·4	9·5	0·15
20	11·2	1·78
	Earth	

1st sect. to fail is J.
At 3 kV/cm, section kV = 33·6.
Corresponding total = 38·6 kV.
2nd sect. to fail is H.
At 2·8 kV/cm, section kV = 27·4.
Corresponding total = 57 kV.
Remaining sections have practically no insulation value, so flashover voltage estimated at 57 kV.

Flashover voltage:	Estimated	57 kV
	Observed	55 kV
Arcing sections:	Estimated	J H
	Observed	A C J H

Insulator No. 3

Max. dia. 12 in
Creepage length 27 in
Total resistance 353·15 MΩ

Sect. res. MΩ	Sect. length cm	MΩ/cm
0·3	7·4	0·04
0·3	4·3	0·07
0·175	7·22	0·02
0·4	6·4	0·062
0·075	5·9	0·013
0·5	6·4	0·078
1·0	4·7	0·212
0·4	6·7	0·06
300	5·75	17·2
50	8·4	5·9
	Earth	

1st sect. to fail is J.
At 3 kV/cm, section kV = 17·2.
Corresponding total = 20 kV.
2nd sect. to fail is K.
Section kV = 25·2.
Corresponding total = 26·8 kV.
3rd sect. to fail is G.
At 2·8 kV/cm, section kV = 13·1.
Corresponding total = 39·8 kV.
Remaining sections have negligible insulation value, so flashover voltage estimated at 40 kV.

Flashover voltage:	Estimated	40 kV
	Observed	39 kV
Arcing sections:	Estimated	J K G
	Observed	J K G F E D A

Insulator No. 4

Max. dia. 13 in
Creepage length 31 in
Total resistance 149·77 MΩ

Contact section Point	(Line)	Sect. res. MΩ	Sect. length cm	MΩ/cm
1				
2	A	20	8·8	2·25
3	B	100	5·35	18·6
4	C	7	4·5	1·56
5	D	1	4·8	0·21
6	E	10	2·4	4·15
7	F	9	8·1	1·12
8	G	0·1	7·35	0·014
9	H	0·2	4·66	0·43
10	J	0·15	3·5	0·43
11	K	0·12	9·3	0·018
12	L	1	4·25	0·235
13	M	1·2	1·6	0·75
		Earth		

Calculations

1st sect. to fail is B.
At 3 kV/cm, section kV = 16·02.
Corresponding total = 24 kV.
2nd sect. to fail is E.
Section kV = 7·2.
Corresponding total = 35·2 kV.
3rd sect. to fail is A.
Section kV = 26·4.
Corresponding total = 54 kV.
Section C's gradient exceeds 3 kV/cm when A fails, and thus C fails without increase of voltage. Similarly F fails when C does. Remaining insulation negligible, so flashover voltage estimated at 54 kV.

Flashover voltage:	Estimated	54 kV
	Observed	55 kV
Arcing sections:	Estimated	B E A F C
	Observed	B E A F C

Insulator No. 5

Max. dia. 9 in
Creepage length 21·5 in
Total resistance 3 910·15 MΩ

Sect. res. MΩ	Sect. length cm	MΩ/cm
100	5·8	17
500	3·72	134
9	4·8	1·86
0·15	5·09	0·029
500	5·09	98
2 000	4·3	465
1	2·15	0·46
800	3·6	222
	Earth	

1st sect. to fail is F.
At 3 kV/cm, section kV = 12·9.
Corresponding total = 25·2 kV.
2nd sect. to fail is H.
Section kV = 10·8.
Corresponding total = 25·8 kV.
B, E and A will all fail successively without further increase in voltage, as their gradients exceed 3 kV/cm.
Remaining sections have negligible insulation value, so flashover voltage estimated at 26 kV.

Flashover voltage:	Estimated	26 kV
	Observed	27 kV
Arcing sections:	Estimated	F H B E A
	Observed	F G H B C E A

Insulator No. 6

Max. dia. 7 in
Creepage length 10 in
Total resistance 1 900 MΩ

Sect. res. MΩ	Sect. length cm	MΩ/cm
0·04	4·8	0·008
0·5	4·8	0·104
0·14	5·9	0·029
0·03	3·75	0·008
1 000	6·0	166
500	3·75	134
400	5·7	79
	Earth	

1st sect. to fail is E.
At 3 kV/cm, section kV = 18.
Corresponding total = 34 kV.
At 34 kV all the remaining sections should fail without further increase in voltage.
Estimated flashover voltage = 34 kV.

Actually this insulator flashed-over under the particularly adverse test conditions at 16·5 kV, owing to corona from the spindle short-circuiting G and F.

Flashover voltage:	Estimated	34 kV
	Observed	16·5 kV
Arcing sections:	Estimated	E
	Observed	E F G A B

* These results apply only to the particular conditions of test for research purposes and should not be considered typical of the service performance of any of these insulators

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(11) APPENDICES

(11.1) Field-Strength Determination with an Oscillating Ellipsoid

The constant K in equation (8) depends upon the dimensions of the ellipsoid, its moment of inertia and the system of units used in the measurements. To calculate K it is necessary to measure these quantities very accurately, but by suspending the ellipsoid in a uniform field of known strength the value of K can be obtained directly by experiment. In this way the constant of the small brass ellipsoid having axes of 0·5 cm and 0·1 cm was determined by suspending the ellipsoid at the centre between two parallel plates each 50 cm diameter and spaced 24·3 cm apart. With 21·53 kV applied, the time for 20 swings was 14·8 sec, whence n_1 was 1·35. The period of free swing was 1·03 sec, so that $k = 1·015$ kV per swing per sec.

The dimensions of the air condenser in which the ellipsoid was tested for behaviour in a non-uniform field were 36 cm radius and 3·75 cm radius for the outer and inner electrodes respectively. A potential of 39·5 kV was applied to the inner electrode. The calculated and observed field strengths at different radii are given in Table 6.

(11.2) Details of Closed-Circuit Wind Tunnel

Cross-section of tunnel = 2 ft × 2 ft.
Mean length of circulation path = 20 ft.
Maximum air velocity = 700 ft/min.

Table 6

Radius	Field strength	
	Calculated	Observed
cm	kV/cm	kV/cm
7·0	1·28	1·30
16·4	0·545	0·545
21·5	0·415	0·405
30·0	0·29	0·26

The chief agent for the production of smoke was the combustion of turpentine and cotton waste in a side chamber. It was not possible to maintain the amount of suspended matter absolutely constant during each test, but samples taken with the suction device used for abstracting a known volume of air showed the amount of suspension to rise to a maximum and gradually fall during each half-hour period. The mean quantity of suspended matter was 1·57 g per cubic metre.

(11.3) The Differential Drying of an Insulator

The non-uniform current density on a disc with electrodes at the centre on opposite sides, results in evaporation taking place more rapidly at the inner radii. In the case of a uniform surface with a potential applied at opposite ends the reason for differential drying is not so obvious but it can be calculated as follows: Consider the surface with resistance ρ per unit length. Let the voltage and current at any point x on the surface be E and I respectively, with a voltage E_l across the whole length l of the film on the surface. Also let C_1 and C_2 be the respective capacitances in parallel with the line and earth. The potential at any point is given by

$$\frac{1}{\rho}\cdot\frac{d^2E}{dx^2} = \omega c_2 E - \omega c_1(E_2 - E)$$

whence $$E = \frac{E_L}{A\sinh A^{\frac{1}{2}}L}[B\sinh A^{\frac{1}{2}}x + D\sinh A^{\frac{1}{2}}(l-x) + D\sinh A^{\frac{1}{2}}]$$

where $A = \rho c_1$; $B = \rho c_2$; $D = \rho(c_1 + c_2)$

$$\frac{dE}{dx} = \frac{E_L}{A\sinh A^{\frac{1}{2}}L}[BA^{\frac{1}{2}}\cosh A^{\frac{1}{2}}x + DA^{\frac{1}{2}}\cosh A^{\frac{1}{2}}(l-x)]$$

When $x = 0$, $$\frac{dE}{dx} = DA^{-\frac{1}{2}}E\coth A^{\frac{1}{2}}l$$

When $x = l$, $$\frac{dE}{dx} = E_1 BA^{-\frac{1}{2}}\coth A^{\frac{1}{2}}l$$

The rate of drying across the moisture surface is proportional to

$$I^2\rho = \frac{1}{\rho}\left(\frac{dE}{dx}\right)^2$$

If τ is the thickness at any point and τ_0 the initial thickness,

then $$-\frac{d\tau}{dt} = k_1\left(\frac{dE}{dx}\right)^2\frac{1}{\rho} = k_2\left(\frac{dE}{dx}\right)^2\tau \text{ (where } k_1 \text{ and } k_2 \text{ are constants)}$$

whence $$\tau = \tau_0 e^{-k_2\left(\frac{dE}{dx}\right)^2 t}$$

or $$\rho = \rho_0 e^{k_2\left(\frac{dE}{dx}\right)^2 t}$$

and dE/dx is greatest at $x = 0$ and $x = l$. Thus it will be seen that the rate of drying is an exponential function of the voltage gradient, and this is greatest at the ends adjoining the electrodes, so that the moisture film will dry out on these parts first, causing a very high concentration of stress and possibly incipient sparking.

THE INFLUENCE OF MAINTENANCE REQUIREMENTS ON THE DESIGN OF ELECTRICAL INSTALLATION EQUIPMENT*

By HAMLYN DRAKE, B.A.†

(*The paper was first received* 18*th September, and in revised form* 24*th December*, 1943. *It was read before the* INSTALLATIONS SECTION *9th March*, 1944.)

(1) INTRODUCTION

This paper has been prepared primarily with a view to pointing out the weaknesses from the maintenance point of view of electrical installation equipment with particular reference to domestic and commercial installations, but there are in addition a few comments on industrial practice the design of which is, in the experience of the author, far more satisfactory.

An endeavour has been made to select from the enormous amount of material available those items which are of the greatest importance, but there must be many other points which either from ignorance or oversight have been omitted, and no doubt the discussion will help to fill the gaps.

In this connection it must be pointed out that the compilation of the paper has been made possible only by the assistance of a large number of people actively engaged in the installation industry to whom the author (who should more properly be called the "editor") is very much indebted.

Maintenance engineers as a class are prone to complain that the design of electrical plant, cables and accessories, switchgear and domestic equipment, though reasonably satisfactory in operation, causes unnecessary delay when repairs are required and unjustified cost which could have been avoided had the designers been more closely in touch with the problems of the maintenance engineer; and it is hoped that the paper may have the effect of co-ordinating to some extent the efforts of these two vital branches of the electrical engineering industry.

Wherever possible an effort has been made to suggest improvements and remedies and to confine suggestions to those which are commercially practicable, but in some instances it may be thought that the extra initial expense is unjustified. The author submits, however, that in many cases the extra cost is well repaid by the reduced maintenance charges during the life of the installation or appliance. It is realized that there may be divergent views on this matter, but the author's point of view does merit serious consideration.

For ease of reference the equipment has been considered under the following headings:—

Switch and control gear.
Cables and cable accessories.
Wiring systems.
Wiring accessories.
Utilization, including domestic, commercial and agricultural applications.
Industrial plant.

In general, complaints fall into four main categories:—

Insufficient space for wiring.
Inadequate terminal arrangements.
Lack of standardization.
Lack of appreciation of the innate clumsiness of the general public.

If manufacturers' future designs overcome these four fundamental difficulties, much perplexity will be saved in the maintenance and installation industry.

(2) SWITCH AND CONTROL GEAR

If manufactured by the better-known makers, switch and control gear, especially when of large capacity, gives little trouble, but there are certain points which are open to criticism.

(2.1) Motor-Starters

To facilitate the replacing of motor-starters, the standardization of fixing centres for various sizes would be of assistance if it could be arranged. This comment applies very generally to all apparatus considered in this paper, and it will be found that the recommendation occurs again and again.

Another general comment which applies particularly to motor-starters is that there is usually insufficient space for wiring. Cables, sometimes of large diameter, are crowded inside the starter case and either become subject to damage by mechanical pressure or foul the operational mechanism. In either event the trouble may not become apparent until a considerable time has elapsed, but the results are nevertheless serious. This difficulty is further aggravated by the fact that terminals are often placed in inaccessible positions thereby causing delays, not only during installation, but also when maintenance or replacement becomes necessary. In the operational mechanism, the contacts are often so inaccessible that cleaning and maintenance are extremely difficult.

The resistance units may sometimes need replacement, and if some method could be found whereby they could be detached without interfering with the starter casing more time would be saved. This feature is already incorporated by some manufacturers, so that to a certain extent it is a matter for selection by the engineer responsible for the specification.

In starters for lower-power motors, thermal protected gear is often incorporated, and this is very apt to get out of adjustment unless the design is such that dust is excluded.

As a final comment it has been suggested that isolating switches incorporated in the starter would be of great assistance, and some commentators have even gone so far as to recommend that this feature be standardized.

(2.2) Industrial Oil Switches

These are generally satisfactory, but tank-lowering gear would be appreciated even on the smaller sizes.

(2.3) Air-break Switches

Air-break switches rated at 100 amp and over are often difficult to install. The terminal arrangements make it almost impossible for satisfactory connections to be made where large v.i.r. cables are employed. These generally enter through the bottom of the unit from a large conduit and then need a double set in a small space to enable them to be spread to suit the terminal spacings. In a triple-pole and neutral unit this is no easy matter, and apart from the waste of time and money involved there is a considerable risk of damage to the insulation unless great care is taken. It is suggested that the terminal block might be arranged in a semi-circle, with the terminals at the circumference of a circle whose centre was the point of entry of the cable.

(2.4) Switch-Fuses

All ironclad switch-fuses should follow the best designs, in which the switch can be mounted either at the top or the bottom of the case. This makes it unnecessary for the incoming cables to cross behind the mechanism. This crossing of cables in a

* Installations Section paper.

† Drake and Gorham, Ltd.

small space is a frequent cause of maintenance difficulties. It has been suggested that all small fixing holes in this and similar apparatus should be tapped and the fixing screws inserted from the front of the case, so that a damaged unit could be replaced without dismantling the complete switch; or, as an alternative, that some form of telescopic mounting should be provided, so that the mechanism could be withdrawn partially from the switch for repair. It is appreciated that the latter suggestion would probably necessitate an excessive first cost and that in spite of the undoubted convenience to the maintenance engineer its adoption might prove too expensive.

(2.5) Flat Back-Boards

It is the normal practice for manufacturers to leave the terminals for the outgoing cables at the back of the circuit-breaker or switch terminals wherever they may happen to be, and provision has to be made on site to support and insulate these outgoing cables or conduits from live metal-work. This is often a costly operation and the final result may leave much to be desired; and if manufacturers could devise a simple method of bringing all connections to a terminal board fixed at the top or bottom of each panel, it would make matters far simpler for the installation and maintenance trade.

(3) CABLES AND ACCESSORIES

These are on the whole satisfactory, and comments are confined mostly to points of detail.

(3.1) Underground Cables

Underground cables give excellent service, and this is no doubt due to the fact that their installation and maintenance have been largely in the hands of the manufacturers; the lessons which they have learnt have been embodied in their designs, thus proving the advantage of close co-ordination between the maintenance engineer and the manufacturer.

There is, however, one suggestion which has often been made but which for some inexplicable reason seems to present an insoluble problem to the manufacturers, namely that a strip denoting the size of the cable should be incorporated inside each length. Such an arrangement would be of very great assistance and would save much time and money.

(3.2) Armoured Cable

Experience has shown that unserved cable for internal distribution is perfectly satisfactory provided proper arrangements are made to avoid caging. If no such arrangements are made, much time is wasted in installation and the final results, even with the very best workmanship, often leave much to be desired. This difficulty can be completely overcome by the use of a superimposed flat helical winding, and any slight extra cost is more than saved in the completed installation. As is well known, there are two main types of armoured cable, one of which has wire armouring and the other steel-tape armouring. The latter has many advantages, and it is simpler and more satisfactory to make use of this type on the larger sizes of cable, but, especially now that the lead covering is lighter than in the past, great care has to be exercised in its use on the smaller sizes, as it is found that if the cable is bent at all sharply there is a tendency for the tape to cut into the lead and cause faults to develop later. This difficulty does not exist if wire-armoured cable is used in the smaller sizes, say up to 0·0225 in diameter.

(3.3) Unarmoured Cable

The extensive use, owing to war-time restrictions, of unarmoured cable underground has caused less difficulty than might have been expected, and many hundreds of miles are now giving satisfactory service with a considerable saving in cost, but it is essential that such cable be adequately served and best results have been obtained by the combined use of paper and hessian.

(3.4) General

Another difficulty, partly from the installation point of view and partly from that of maintenance, has arisen because the colours of the cores have not been standardized. For instance, in some four-core cables red, yellow, blue, and striped colouring are used, whereas in others red, yellow, striped and black are used, the striped core usually being specified as the neutral in the first case and as the blue phase in the second.

It is suggested that the same colour should be standardized and used throughout the installation and that it should apply to cables, busbars, sub-circuits, and small wiring. Such an innovation would considerably simplify the work of the maintenance engineer.

It is understood that a modification of B.S. 158 is contemplated and that this would incorporate the above suggestion.

(3.5) Underground-Cable Boxes

These accessories are on the whole satisfactory provided that they contain an inner lead sleeve to which the lead covering can be wiped, thereby making a completely watertight joint. If the lead sleeve is omitted there is always a danger of moisture entering at the boxes and causing a breakdown. Such boxes are already in existence, but from the installation point of view it would be a great convenience if there could be more standard sizes of sleeve. At present, where the lead sleeve is too large it requires a great deal of dressing down, and if the cable is too small there is a considerable amount of making up to be done; in both cases time is wasted.

The only other criticism, which is almost universal, is that the compound filling hole is too small.

(3.6) End-Boxes

These are generally satisfactory, but it is not always possible to obtain boxes of one particular make and it is therefore essential that the flanges and fixing centres be standardized.

(3.7) Inverted End-Boxes

The usual practice is to use an ordinary end-box with a plate made of plywood drilled on site to take the outgoing v.i.r. tails, but this system is not always satisfactory, especially where the ambient temperature is high, and there is a great need of a standardized box specially designed for inverted use with an oil and compound seal at the base. At present such boxes must be made up specially.

(4) WIRING SYSTEMS

Wiring systems, of which there are eight important types at present in use, are considered separately. All of them have good and bad points, and some skill is required in selecting the most suitable for any set of conditions.

(4.1) Screwed Steel Conduit

This appears to be the most generally approved system of wiring at the present time in this country, provided that it is properly installed and that satisfactory continuity is assured. The use of graphite grease on all screwed connections has been advocated, and this is of special importance where conduits are buried in concrete. Where connections have to be made to adjustable grid boxes and similar equipment without screwed-spout entries, the brass-disc washer has also been of value.

Trouble has sometimes been experienced in the use of galvanized conduit owing to spelter being left inside the galvanized tube and damaging the insulation when the cables are drawn in. Sherardized conduit overcomes this difficulty.

It is essential that great care be taken in the manufacture of

conduit to ensure that the external size is uniform, so that time is not wasted in threading; and a more uniform standard of hardness is required, so that bends may be made accurately at the point where they are required and not at some other point where the metal is soft. Little difficulty has been experienced in this respect in recent years, but at one time it was a serious cause of complaint.

(4.2) Grip Steel Conduits

There appears at the moment to be a school of thought which favours the increasing use of this method of installation, but the continuity of pin-grip fittings is most uncertain and lug-grip fittings, while reasonably satisfactory if properly installed, show little saving in cost over a screwed-barrel installation, especially if the general propensity for using an excessive number of fittings is indulged.

(4.3) Copper Conduit.

This system has many advantages over any other. Condensation troubles are almost non-existent and, even if they do occur, they do not, as in the case of steel conduit, form a compound which is deleterious to the rubber insulation. A further advantage is that, under the above conditions, rewiring is immensely simplified. In steel conduit, when rusting has occurred it is often virtually impossible to withdraw the wiring and replace with new.

(4.4) Lead-covered Wiring

This seems to be a generally accepted system, but unless an earth wire is incorporated there are continual complaints of loss of continuity owing to the poor design of the continuity grips and the softness of the lead. It has, however, the inherent disadvantage that unless protected from mechanical damage the lead may become dented, thereby putting the rubber insulation in a state of compression which forms a potential weakness liable to cause serious trouble at a later date.

Incidentally, it would be of assistance if some form of rat poison could be incorporated in the lead to avoid the ravages frequently caused by these rodents.

(4.5) Tough-Rubber Sheathing

Tough-rubber installations have many advantages particularly if an earth-continuity wire is installed, but mechanical protection must be provided, and for new buildings it is suggested that light conduits and cast-iron boxes should be installed between the floor and roof spaces for all switch and plug positions. The cable could then be drawn in afterwards, satisfactory earthing being provided by bonding the earth wire of the t.r.s. to the back of the outlet boxes.

(4.6) Mineral-insulated Wiring Systems

These have proved most satisfactory in damp situations or where the ambient temperature is high, but existing methods of sealing-off the ends of the cable require simplification and improvement. At present it is exceedingly difficult to detect faulty joints at the time of installation and in damp situations the fault may not appear until three or four months after the work has been completed.

(4.7) Duct Systems

Duct systems have been adopted extensively for large office buildings and similar situations, and have proved satisfactory except that there is great scope for further development in the design of the various outlet boxes. Extreme accuracy is necessary to ensure that the outlets are flush with the finished floor level, and all outlet boxes should be provided with a simple and inexpensive method of adjustment of at least $\frac{1}{2}$ in to meet the usual and apparently unavoidable variations.

If the system is to be entirely satisfactory it is essential that there be the fullest co-operation between the architect, the consulting engineer and the electrical contractor, and the cost is greatly reduced if provision for the ducting, particularly in vertical runs, is provided in the building construction. In large buildings the vertical risers can be in the form of busbars, and hardwood or metal doors should be provided at each floor to give ready access.

(4.8) Copper Concentric Earth-Return System

Experience has shown that if properly installed this system is virtually trouble-free. Faults are easily located, and owing to the nature of the design, adequate earthing and bonding cannot become defective; any fault is bound to blow the fuse. Unfortunately, the system can be used only with private generating plants or in the comparatively few cases where supply authorities allow multiple earthing on their system, but apparently it is considered that in the majority of cases multiple earthing would cause difficulties, though where it has been adopted experience seems to disprove this view.

(4.9) Flexible Conduits

Where these are used to connect to motors or other equipment, there is a general complaint that there is no satisfactory form of adaptor, and unless the flexible tube is sweated continuity cannot be assured. If a satisfactory adaptor could be provided, factory inspectors might be persuaded to dispense with the independent earth wire that is at present obligatory.

(4.10) Bell Wiring

Bell wiring is always unsatisfactory unless carried out with good-quality rubber-insulated cable. There are still many bell installations wired with cotton-covered cable which are an absolute plague to maintenance engineers, and the comment is often heard that owing to this cause alone the bells give far more trouble than all the rest of the installation.

(5) WIRING ACCESSORIES

Under this heading there are a multiplicity of small items, many of which are far from satisfactory, and more space has therefore been devoted to this section than to others.

(5.1) Main Distribution Boards

Installation and maintenance would be far easier if all manufacturers would standardize the sizes of cases for the various ranges of boards, the cases being so designed that switches, switch-fuses and cable end-boxes could be fixed direct to the tops or bottoms of the boards.

Here, again, terminal arrangements are difficult. The incoming cables may be 19/0·083 in or larger, and there is seldom sufficient room for these connections to be made without danger of damaging the insulation. A suggestion has been made that in all sizes of fuse-board more room would be available if the cable lugs were placed on the extreme end of the busbars instead of staggered as at present. This criticism applies principally to the cheaper-quality boards.

Another cause of frequent complaint is that the neutral bar is inaccessible and often appears to have been added as an afterthought and tucked away somehow in the only corner where there is room for it, regardless of the fact that it serves a useful purpose.

Now that high-rupturing-capacity fuses are being used so universally it would be of material assistance if all fuse-bridges were designed in such a way that this type could be used.

Where barriers are placed between the poles the material used is often mechanically weak, or at any rate brittle, and liable to break away at the fixings. This is a frequent cause of trouble and more adequate means of support are required.

(5.2) Sub Fuseboards

Here, again, sufficient space is seldom allowed for wiring, so that the usual increased maintenance costs are involved, and comments are much the same as those on main distribution boards except that the use of pressed steel or fabricated cases is favoured. These are lighter to handle, fixing is an easier matter, and knock-out holes can be provided to receive the conduits or glands required; a similar hole for the incoming main should be provided at the top as well as the bottom of the board.

Standardization of fuse centres and small fittings would be a great advantage, and a further suggestion has been made that where earthing lugs are required they should be connected by two fixing screws instead of one in order to avoid the danger of the connections working loose.

Finally, captive screws save the maintenance engineer a deal of time. The non-captive type are easily dropped, and tempers become frayed in looking for them.

(5.3) Porcelain Fuses

There must be a large potential demand for a porcelain fuse which is capable of being wired by a reasonably intelligent human being in under an hour. Most of the existing designs require the services of a clock-maker, with more than the usual complement of hands, when they need attention.

In any case, provision should be made for the fuse wire to go under a rigid clamp and not under a washer; the latter tends to turn with the screw with the result that the wire is tightened and breaks, and this generally happens after one end has been satisfactorily anchored, so that still more time is wasted before the fuse is rewired. To simplify the work of the maintenance engineer (particularly when he is called in after members of the public have been indulging in amateur efforts), it is further suggested that all fuse-carriers be fitted with a flat disc on which the size of the fuse wire to be used is indicated by the contractor who carries out the original installation, so as to avoid the use of incorrect sizes in the future.

All sizes of fuse wire should be listed under safe carrying capacity and not as at present under fusing current.

(5.4) High-Rupturing-Capacity Fuses

This type has proved most satisfactory, but much time and money would be saved if the centres were standardized. This is particularly necessary in factory installations where machine-tool makers often supply with their machines, control equipment incorporating h.r.c. fuses of a make different from that standardized in the rest of the factory.

There is a demand for a h.r.c. fuse which gives a slight time lag to deal with initial surges due to the starting of motors or the switching-on of large banks of gas-filled lamps. The silver-wire type of fuse does not at present comply with this requirement. Apart from this criticism and if they could be produced at a low price, h.r.c. fuses would surmount nearly all the difficulties at present experienced with the porcelain type and would to a large extent remove the danger occasioned when a member of the public completes a faulty circuit with a hairpin.

(5.5) Small Circuit-Breakers

From the maintenance engineer's point of view, there is no doubt a great deal in favour of the use of small circuit-breakers to replace the usual 5-amp fuse, and fuses could be entirely dispensed with if one which would operate satisfactorily could be produced at a reasonable price.

(5.6) Tumbler-Switches

There is room for much improvement in this accessory, particularly in connection with standardization, which should apply not only to fixing centres but also to terminal positions. Under present conditions, the maintenance engineer must either carry renewals of many different makes or adapt existing fittings to the make which he has with him. As an example, a 5-amp switch for mounting in an iron box may at present have fixing centres varying from $1\frac{5}{8}$ in to $2\frac{1}{16}$ in. The fixing screws may be either B.A. or Whitworth, and the box either shallow or deep. Furthermore, if the terminal entry is different in surface switches, blocks may have to be taken down, redrilled and refixed before a faulty switch can be replaced, with the additional difficulty that if the vulcanized rubber has become brittle with age, any disturbance will cause it to crack and give trouble.

So-called 5-amp switches should be more robust and capable of carrying a 5-amp current. This is particularly necessary where they are controlling 5-amp plugs which can be used up to their full capacity. Experience has shown that existing 5-amp switches can be relied upon to break currents up to 3 amp only.

Switches of the quick-make/slow-break type materially reduce the maintenance costs, but in the author's experience this type of switch is virtually, if not totally, unobtainable for intermediate use; and trouble has been experienced with intermediate switches of the quick-make-and-break type owing to their flashing-over when controlling circuits of half a dozen 60-watt 230-volt lamps.

Switch terminals are in many cases too small to allow for satisfactory looping; larger ones would be welcome.

Terminal screws are also a weakness and are apt to strip unless great care is exercised in installation. The practice of setting them at an angle has been of much advantage to the maintenance engineer.

Adjustable boxes for use with flush-pattern tumbler-switches are generally far too cramped and often lead to the wiring being pinched behind the grid. The fault may not develop for months or years, but more room in the initial installation would overcome the difficulty. In carcase buildings, where wiring has to be installed before the application of the plaster, there is often a gap between the edge of the box and the finished plaster wall, and the author wishes that some inexpensive arrangement could be provided in all boxes whereby the switch mechanism could be totally enclosed in a metal structure.

(5.7) Switch-Plugs

Trouble has been experienced with the switches of 2-amp switch-plugs, due to the lightness of the switch contacts. A heavier design is urgently required. Also, why is it that a switch-socket incorporating a quick-make/slow-break switch is apparently unobtainable?

In the interlocking type interchangeability is not yet satisfactory in spite of the work of the B.S.I., and efforts are required to see that this is rectified.

(5.8) Plugs and Sockets

The terminals of some makes of plug top are too small to take flexible cords having a current-carrying capacity as high as that of the pins. In any event the recessed-washer and nut type of terminal is much preferred as it avoids the danger of cutting the flexible cord when making the connection.

A good cord-grip is essential, especially for use with 3-core circular flexible cords. It is realized that this increases the initial cost, but where it is not provided maintenance costs are very much increased.

It is noted with satisfaction that it is proposed to dispense with the 2-amp plug. This accessory has caused maintenance difficulties and is prone to overheat at anything like its normal rating.

If new plugs are to be standardized, the author earnestly hopes that consideration will be given to the standardization of a flat-pin type as used with success both in America and on the Continent. With this type of plug it is possible to obtain good contact without making the fit so tight that the plug cannot be

withdrawn without considerable force. Furthermore, this type simplifies the question of using varying sizes of plugs (suitably fused) in one size of socket. It is admitted that the foreign products are not things of beauty, but they are cheap and seem to give no trouble—both points of some importance.

More sockets are mounted on or near the skirting than anywhere else, and manufacturers should pay more attention to wiring. It would be of considerable assistance if the interior could be removed in such a way that the wiring could be carried out clear of the box, a deeper box being provided to take the slack and to prevent pinching the conductor between the unit and the back of the box. Two obvious objections to this suggestion are that where maintenance is required after some years, damage may be caused by disturbing wiring which has become brittle, and that more cutting away will generally be necessary.

Provision must also be made for looping, as it is becoming more and more common to use socket-outlet boxes as draw-in boxes, and this again emphasizes the necessity for providing adequate terminals.

If sockets are not to be controlled by switches, some form of shutter is most desirable.

(5.9) Ceiling-Roses

There is probably no accessory which has caused more irritation to installation and maintenance engineers than ceiling-roses. Manufacturers often forget that they are normally attached to ceilings and that work must be done upon them standing on a ladder and working above the head. It is therefore essential that all terminals should be of more than adequate capacity, not only to assist looping but also to provide ease of connection. The usual non-captive small screws which are generally dropped two or three times before being satisfactorily engaged are a bugbear, and alternative methods must be standardized.

The three-part ceiling-rose is unsatisfactory where the terminal base is not directly fixed to the ceiling block or conduit-outlet box. When flexible cord has to be renewed the v.i.r. cable also has to be moved and at this point it tends to become brittle at an early stage, especially where central heating is installed. This has proved to be a frequent cause of trouble. The same applies to the semi-recessed type which fits direct into iron boxes.

A ceiling-rose incorporating a socket-outlet to which the flexible cord can be connected, dispenses with many difficulties and has a number of advantages.

(5.10) Lampholders

A number of points in the design of lampholders call for comment. In practically all designs shade-carrier rings show a marked tendency to become tight after they have been installed for some time. Not only does this cause waste of time but shades are frequently broken. The use of lugs improves matters but is by no means an infallible cure.

Terminals are another source of irritation. In certain cases the wall thickness, especially if the screws are mounted at an angle, is totally inadequate and results in insufficient threading, which constantly strips when screwed up tightly. Furthermore, where lampholders are connected direct to conduit or used as batten-holders, it is essential that the terminals be large enough to allow for looping.

It must be borne in mind that lampholders in which the terminals are firmly fixed to the movable pillars must not on any account be attached to v.i.r. cables.

One last general comment refers to switch-type holders. These are almost universally unsatisfactory owing to the fact that everything is sacrificed to neatness. It is submitted that it would be far wiser to provide a switch-type holder of more robust design which could be relied upon to operate for a longer period.

Metal lampholders are otherwise satisfactory but they should be provided with a visible earth connection. The only other complaint is that the porcelains are too weak and are often broken even in replacing lamps. This criticism refers particularly to Edison-screw types but is not entirely absent throughout the range.

On plastic lampholders there are three main comments, the most important of which is that the plastic material is insufficiently reinforced so that the lampholders are too prone to break at the bayonet sockets. Where they are used on insulated standard lamps the spouts need reinforcement. The present type is perpetually breaking at this point and is most unsatisfactory in this respect. Some plastic holders have no stop ring between the cap and the shade-carrier ring, with the result that when unscrewing the latter there is a tendency for the whole assembly to disintegrate and cause unnecessary waste of time before it is possible to resume constructive activities.

In Goliath holders, especially those used for lamps of 750 watts or over, there is need for improvement. The metal-work should be stouter and the centre contact fed by means of copper pigtails. The springs used for tensioning purposes are subject to considerable heat and cannot be relied upon to carry current for more than a comparatively short period.

(5.11) Lamp-Caps

It would be a great advantage if all lamp-caps could be made of an all-insulated material. On modern installations where lampholders are earthed, serious faults have resulted from short-circuits between the solder connections at the base of the lamp and the cap. The path between the terminals and the cap is so short that low insulation readings are often obtained, and the source of the low readings is very difficult to trace. In large installations it is frequently impossible to remove lamps before insulation tests are taken.

(5.12) Fittings

There is such a large variety of equipment under this heading that it is impossible to deal with it satisfactorily and it only remains therefore to make the general statement that in far too many cases the space for wiring is inadequate, and it is often impossible to use heat-resisting cable where conditions make this desirable. In some cases it is even necessary to strip down to the vulcanized-rubber insulation in order to get up to the lampholder, and such an arrangement is bound to cause trouble in the long run.

There is a tendency, especially in the cheaper grades, to allow far too much weight to be carried by flexible cords, and maintenance difficulties would be considerably reduced if chains for carrying fittings were applied to smaller sizes than is at present standard practice.

Where portable fittings with bushed holes are provided, the latter are often too small to take three-core flexible cord, which should always be used where metal fittings are installed, and difficulties in installation are caused thereby.

The provision of visible earth connections on metal fittings is an essential point often overlooked by fittings designers.

Fluorescent fittings are at present comparatively in their infancy, and difficulties are sometimes caused by the lamps themselves varying in length. Closer standardization is essential if maintenance difficulties are to be reduced to a minimum.

With external fittings, insufficient care is usually taken to avoid rust. This applies particularly where the fittings are to be installed near the sea. Protective paints which are now on the market should be used to undercoat all such fittings, and this work should preferably be done before they are despatched from the works, particular care being taken to ensure that all threaded joints are properly dealt with. If this is not done at the works it is vital that it should be done by those responsible for the

erection immediately the fittings are erected, and not, as so often happens, when the installation is complete. Ordinary stove enamelling is unsatisfactory; it is too brittle and has a marked tendency to flaking.

(5.13) Bell Accessories

Bell-transformers are sometimes fused only on the primary side. This causes difficulties, and fuses on both primary and secondary sides are preferred. It has been suggested that all bell-transformers should be housed in light pressed-steel cases instead of the more usual all-insulated finish. This would facilitate bonding, and installation would be simplified if knock-outs were provided so that an efficient earth connection could be made between the conduit and the case of the transformer.

Decorative bell-pushes are frequently made to take only the very small cotton-covered twin bell-flexible which is not very robust, and causes maintenance troubles. Provision should be made to take standard circular twin with suitably bushed entries to the pushes, and proper cord-grips are essential.

It has been noticed that composition pushbuttons if used in damp positions tend to swell and stick. More clearance is therefore required where this material is used.

There is a demand for a satisfactory watertight-pattern push of reasonable dimensions. High-voltage, non-watertight pushes of the switch type are available in standard conduit switchboxes, and a similar pattern incorporating watertight features and of similar dimensions would fulfil the demand satisfactorily.

(6) UTILIZATION

Utilization covers those items which from the maintenance point of view give the most trouble because they are normally in the hands of people totally unskilled and ignorant of all engineering practice. This particularly applies to domestic appliances, and it must be appreciated that the troubles are due not so much to bad design as to design unable to withstand bad handling.

In general, designers do not appear to appreciate that the great British public whom they serve are for the most part entirely unmechanical and apparently endued with the proverbial strength of the lunatic, so that what would appear to the engineer to be a satisfactorily robust design is totally incapable of withstanding the normal treatment which it is expected to meet in the British home. It cannot be stressed sufficiently strongly that designs which would be perfectly adequate in the workshop or factory have a ridiculously short life in what would at first sight appear to be an easier situation.

Flexible connections to portable appliances are a case in point. Whatever type of cord is used the cord-grips are usually inadequate, and the number of faults that are caused and the cost of maintenance incurred due to this alone, make it imperative that more consideration be given to design. The moulded-rubber ends frequently supplied with electric irons appear to be the best solution so far, but even these do not appear to be sufficiently foolproof.

(6.1.1) Kettles.

There are many types of kettle on the market incorporating a safety device to protect the kettle if the current is switched on when it is empty. This is an essential feature but it must be of the quickly replaceable type in view of the frequency with which it is called upon to operate.

In kettles in which the element is clamped to the bottom there is a tendency for the bottoms to warp, so that when new elements are fitted it is impossible to make a good mechanical contact, which again causes the elements to burn out. The bottoms should be much more robust.

In certain hard-water districts, the water reacts with solder, and brazing is preferred for this reason.

(6.1.2) Electric Irons.

If improperly handled, electric irons are a great source of danger as it is so easy to forget that they are switched on. This can be guarded against to some extent by installing indicator lamps, but these are frequently ignored and some form of thermostatic control should be made obligatory.

Plastic and porcelain tops are pleasant to look at and to use, but they are fragile and expensive to replace; more reinforcement is required.

Trouble has been experienced due to the porcelain insulators which support the thermostat being too flimsy. If these were insulated with mica, it would overcome the difficulty.

Maintenance costs are frequently incurred owing to the iron being put down on the flexible cord, and there would appear to be scope for a domestic iron designed on the lines of the type frequently found in laundries, to which the current is applied only when it is safely on a stand, the iron being removed from the stand while it is in use and having no electrical connection whatever.

(6.1.3) Vacuum Cleaners.

There is probably no more abused form of apparatus than electric vacuum cleaners, and it appears to be impossible to make the public realize that they do not work on the same principle as floor sweepers, which require to be moved rapidly across the carpet. The consequence is that they are constantly being bumped against skirtings and furniture until every nut and bolt (of which there appear to be too many) has been shaken loose, leading to endless maintenance charges. The bearings are seldom, if ever, lubricated, and the bags are not emptied sufficiently often.

It is therefore suggested that more care should be taken to provide nuts of the locking type, and the maintenance engineer's troubles would be much simplified if these could be all of one size.

Self-lubricating bearings should be employed to a much greater extent.

The orifice leading to the bag should be of ample dimensions, as troubles are frequently caused by this becoming blocked owing to the bag being emptied at too infrequent intervals.

A frequent cause of trouble is the control switch, which is generally too small and restricted. Time and temper would be saved if this could be installed in a through-way insulated outlet box with a normal type of switch utilized for the purpose.

In general, the parts needing repair, particularly the motor, are too inaccessible, and the whole machine has to be dismantled for some minor repair. There is great room for simplification, and maintenance engineers complain that they require the limbs of an octopus and the patience of Job.

(6.1.4) Electric Cookers.

From the maintenance point of view, these appear to be reasonably satisfactory except in certain types of boiling rings. It is absolutely essential that these should be quickly and easily replaced since they usually have to operate under a cataract of water and/or grease.

(6.1.5) Space Heating.

There are a number of systems of space heating and it is not the province of this paper to discuss their merits or demerits, but whatever system is employed the switch control should have some visible indication as to whether the heaters are in operation. Tubular heaters are frequently arranged in tiers, and certain existing methods of connection are awkward and cause considerable difficulties; it is almost impossible to know whether connections have been satisfactorily made, and in any case the space is too cramped. This refers particularly to flame-proof types.

Thermostats.

These are often enclosed in cases of insulating material which

although made for conduit entry make earth continuity a difficult problem. Metal boxes are therefore preferred.

(6.1.6) **Electric Fires.**

These are generally so made that the connections are inside the casing. It is impossible to see whether earthing has been satisfactorily carried out, and when the maintenance engineer has to replace the flexible cords it is necessary to dismantle a large part of the fire. As faults usually occur inside the casing at the terminal ends, they are difficult to locate. A connection box with a satisfactory cover on the outside of the fire would be a great improvement; or, as an alternative, a reverse plug and socket enabling the flexible cord to be removed when not in use would have many advantages.

(6.2) Commercial and Industrial Apparatus

On the whole, commercial and industrial apparatus gives far less trouble than that in the hands of the general public, and few suggestions have been made.

(6.2.1) **Permanent-Waving Apparatus.**

This is surprisingly satisfactory, in view of the conditions under which it has to operate, but there is room for improvement in the flexible connections.

(6.2.2) **Portable Tools.**

These give little trouble, provided a satisfactory flexible cable is employed, preferably heavy t.r.s. with steel-wire braiding which could perhaps be used as an earth conductor. Earth connections on all tools should be visible and very robust. Connection to the circuit wiring should be by means of a plug with a screwed fixing ring so that it cannot be pulled out.

(6.3) Rural Installations

Unfortunately rural electrification is not yet on a sufficiently large scale to provide much opportunity for criticism and suggestions, but the maintenance engineer would like to impress upon manufacturers and consultants responsible for the design of rural installations that they will usually be operated by farm labourers who, although skilled workers in the truest sense, are accustomed to very robust apparatus such as ploughs and horse rakes, and whose knowledge of the use of mechanical small tools is usually confined to the hammer. All apparatus must therefore be of the very simplest and with as few exposed moving parts as possible.

Furthermore, motors for use with agricultural machinery will generally be installed in places where there is inevitably dust and chaff, or in dairies which though spotlessly clean have a humid atmosphere; it is therefore strongly recommended that all motors should be of the totally-enclosed type or, at any rate, dust-proof, and they must be liberally rated as they will almost certainly be subject to considerable overloads from time to time.

A standard specification for agricultural motors is urgently required, especially in view of the greatly increased demand to be expected after the war.

The same general principles apply to the installation of electric sterilizers and other dairy equipment, and watertight fittings should be used thereon if maintenance costs are to be kept low.

It is submitted that there is great scope for development in the use of electricity on farms for all purposes, and grass-drying must not be overlooked. On the poultry farm there are endless opportunities for incubators, brooders, and the like, and the application of ultra-violet rays for both poultry and cattle gives further scope for specialist application. In the market garden also, electric heating has proved successful both for greenhouses and soil heating, and research has been carried out on the effect of high-voltage discharges for the improvement of crops, but at present the maintenance engineer has insufficient experience except on general lines to be able to express definite opinions.

In rural installations for agricultural purposes the safety factor is of prime importance, owing to the susceptibility of all animals to electric shock, and there is much to be said for the use of three-phase step-down transformers to give a maximum voltage between phases of 100, with 57·8 volts to earth. Even at this figure there is still danger, and this can perhaps best be overcome by the more extensive use of earth-leakage trips, a practice which has been successful for many years on the Continent.

(7) INDUSTRIAL PLANT

Although perhaps not strictly within the scope of the paper, there are a few general remarks on industrial plant which may prove of value. In general, there is far less room for adverse comment on this class of apparatus than on the electrical gear already discussed.

(7.1) Motors and Generators

On the whole, few difficulties are found in dealing with the medium- and larger-size machines, but the terminal boxes are in almost every case too small. They should be made in such a way and of such a size that it is possible to accommodate the connections with ease, and so that screwed conduit, cable-end boxes or glands for cambric-insulated cables can be coupled direct to the box.

Further, it is strongly recommended that terminal boxes should be fixed in a standard position on the motor frame.

Here again, much time would be saved if the marking of the terminals could be standardized.

It is a great help when terminal boxes are so made that they rotate and enable entry to be made from a variety of different directions. Maintenance is also much assisted if captive milled-head screws are used to hold the cover-plates, instead of the hexagon- or slotted-head screws which are frequently employed at present.

In some designs oil drainage from the bearings leaves much to be desired, and many troubles are overcome if the surplus oil returns to the well without escaping from the bearing end.

The maintenance engineer often has to change one motor for another where repairs are required quickly in order to avoid loss of output in the factory, and it is not always possible, especially under war-time conditions, to obtain a motor of the same make and type at short notice. At present there is little standardization in the main essentials, such as shaft diameter or height of centre of shaft and fixing holes, and the inconvenience and waste of time which this causes would be eliminated if these essential dimensions were agreed upon between all manufacturers.

In fractional-h.p. motors it is necessary to test the gap between the rotor and stator, and in totally-enclosed machines this is impossible unless suitable holes with spring covers or the equivalent are provided by the manufacturers so that a feeler can be inserted.

(7.2) Welding Generators

The present practice for rating these machines by temperature rise causes difficulty, as one which does not overheat under load may be subject to flashover, and it is difficult therefore to know whether it will deal satisfactorily with any particular welding load.

The flexible leads are usually fastened to the generator with a thumb screw. This would be perfectly satisfactory if operators could be relied upon to tighten it up correctly, but maintenance experience has shown that this is not always done, and a device which will either lock tight or not at all, as standardized by one manufacturer, appears to be the best solution.

(7.3) Metal-Oxide Rectifiers

These are satisfactory, but experience has shown that they must be protected by quick-acting fuses. Standard fuse wire is unsuitable.

(7.4) Batteries

From the maintenance point of view batteries are generally satisfactory, provided that adequate capacity is specified in the first instance. There is a tendency in certain makes for the positive lugs to give way, and these could with advantage be strengthened.

(8) CONCLUSIONS

In preparing the paper, comments have been based on experience gained with existing equipment, but it must not be thought that the author is entirely in favour of expensive material, made more expensive by the necessity for enabling repairs to be carried out quickly. There is much to be said for equipment on simple and robust lines made in the cheapest possible way with no facilities for easy maintenance, but if this method is adopted the price must be such that in the event of trouble the whole unit can be scrapped and replaced. This presupposes a high degree of standardization which from the maintenance engineer's point of view is perhaps the most burning question of all. Much of the delay and irritation that is at present caused is due to the non-interchangeability of components of similar capacity supplied by different manufacturers.

If standardization on these lines can be achieved, many of the maintenance difficulties will disappear and the amount of capital which at present lies idle in the stores of maintenance contractors, owing to the necessity for storing a multiplicity of types, will be released and utilized in more useful channels.

It should surely be possible for standardization to be arranged in such a way that the individual features and designs of manufacturers could be incorporated within the framework of the main fundamental standardized dimensions, without cramping the ingenuity and individuality of designers. Many specifications today seem to operate in the reverse direction by limiting the individual talent of designers without providing interchangeability.

In drawing up standard specifications, it must be remembered that as the electrical installation trade has developed there has been a steady increase in the ratio of the cost of labour to the cost of material, and manufacturers may to some extent have lost sight of this important factor in their desire to reduce the cost of electrical accessories and fittings. Labour costs on site are still rising, and it therefore becomes more than ever important to provide material and equipment which will reduce costs to the minimum; many of the criticisms in the paper are based on this fundamental principle.

Finally, the author wishes to emphasize the fact that in preparing the paper he has been looking for trouble, and it must not be supposed from the conclusions drawn that all equipment is fundamentally bad in design. A large quantity of the equipment supplied by manufacturers has reached a high degree of perfection, but no industry is perfect and it is hoped that the author's criticisms and suggestions may be of some assistance to manufacturers in planning new designs for use in the post-war reconstruction which we all hope will soon be upon us.

DISCUSSION BEFORE THE INSTALLATIONS SECTION, 9TH MARCH, 1944

Mr. Forbes Jackson: It is true that there is a certain divergence of interest between the manufacturing side and the using side. Too many of us on the using side specify the things that only we want, and the manufacturers have so many requests for "specials" that they discount any criticism; even fair and reasonable criticism is often not accepted, because the manufacturer is used to criticism that is neither fair nor reasonable. I have found it almost impossible to persuade any manufacturer at any time that his article was not perfect. That may have been because it was perfect or because I was not sufficiently persuasive; but the fact remains that manufacturers are not very responsive to comments from the user.

A suitable apparatus may be chosen and used satisfactorily for years. Then its manufacture is discontinued and it is replaced by another accessory which does not give the same satisfaction as the previous model. Similarly, some small and quite reasonable cheapening process may have been adopted; e.g. a screw in a porcelain base was recently replaced by a rivet. This was a trivial alteration which the manufacturer did not feel called upon to mention, and I should not have commented on it had I noticed it at the time; but by the time several thousand had gone into service and the porcelain bases had begun to crack, I realized that this small change had let me down on a piece of apparatus in which previously I had put a good deal of faith.

Is there any remedy for what may be called innocent mistakes on the part of the designer, who is perhaps not altogether familiar with all the conditions under which a piece of apparatus is to be used? In other words, how can we get this collaboration which the author suggests? I think that it will prove difficult. The more committees that are set up, the more we seem to go round in circles. I have asked myself whether the British Standard Specifications could be enlarged to deal with points of this sort. I do not think that they could.

I wonder whether the E.C.A. are not in the best position to deal with the problem, by starting a list of approved materials. Any competent engineer feels that he can judge from the look of the average piece of apparatus whether it is going to suit his purpose or not, but there may be hidden defects which do not become apparent until later. If the E.C.A., by collaboration among their members, could circularize a statement that a particular switch was unsatisfactory, this might bring home to the manufacturer that his switch was not very good, whereas an individual complaint would be met by a brusque rebuff. I commend the idea to the E.C.A.

In Section 4.2 the author says that there is a school of thought which favours the increasing use of the grip-joint conduit. I seriously recommend any contractor who wants to get into the housing business to study the merits of grip-joint conduit with brazed or welded tube. From a very long experience with it, I find it enables the cost to be cut by at least 20% and gives a perfectly satisfactory job as compared with screwed-barrel conduit.

Whichever system of wiring is used, if it is put in properly and is in a reasonably dry situation, it will not give much trouble. The trouble is almost always with the accessories, and it is because these have to be taken off and put on again so many times in the installation's life that the ends of the wires ultimately go. Capping and casing jobs last 40 years, while good conduit jobs may last only a few years. In a dry situation almost any job will do if the ends are treated properly. That being so, I wonder whether a range of boxes could be developed in which the ends or the loop of every wire were brought to a fixed terminal in the box, and the accessory attached to it by a short length of wire. That would get rid of many problems, and the wiring would not be spoilt when the accessory was changed.

The day-to-day maintenance of small installations in houses and commercial buildings consists almost entirely of sending a man to change a switch, socket or flexible; the cost of sending the man to the job is actually very much greater than the cost of the material entailed by the repair, while the time he takes in doing the work is very small. We should therefore aim at keeping the fixed part of the installation as simple as possible, and for that reason I favour flexibles which can be unplugged from the ceiling, so that the consumer, if the flexible goes wrong, can unplug it and take it to the company's depot to get it re-

paired. Flexibles would then not be fixed on to fires but connected to them by plugs.

The author says that his experience with 5-amp switches is that they do not carry the current; that is a general experience. He also states that in designing a new socket for domestic purposes we should start *de novo* and do the best we can. I think we all agree that one socket is desirable for domestic purposes, but there is still a good deal of doubt as to what that socket ought to be. Almost the whole of the using and installation side of the industry believe that nothing but confusion and trouble will arise if we try to up-rate the 5-amp plug; up-rating is apparently being pressed on us, against our better judgment, by other people not intimately concerned with utilization and installation. If this goes on, in a few years' time we shall arrive at the very state of affairs of which the author complains, namely excessive maintenance because the views of the installation people have not been heeded.

Mr. H. J. Cash: I am a strong believer in the future of copper conduit, because before the last war I made wide use of the Kalkos system, which was tinned brass tube with a thin wall, with a high heat conductivity, so that the temperature inside and outside was almost balanced and condensation was unknown. Recently I inspected jobs carried out on that system over 35 years ago; they looked like lasting another 35 to 50 years. Certainly no other system which we have adopted has approached it for durability and freedom from maintenance.

In Section 4.5, the author says that mechanical protection must be provided for tough-rubber installations. This seems to me against all experience as this brand of rubber is not harmed by even the roughest use.

I am glad that in Section 5.4 he recommends that a h.r.c. fuse should have a slight time-lag. In my opinion, the installation industry is heading for trouble by its ill-considered assumption that the h.r.c. fuse is the fuse of the future. Its drawback is that it ruptures instantaneously. The supply undertaking wants the high rupturing capacity which has been provided by quick action, but the consumer wants not quick action but a reasonable time-lag, such as is provided by a cartridge fuse with a copper fuse-element.

In Section 5.8, the 2-amp plug is said to be prone to overheating at its normal rating. I believe that any good manufacturer of a standard 2-amp plug will claim that it can be loaded up to 4 amp; it has the highest margin of safety of any electrical accessory. I agree with the author's demand for a deeper box to receive the socket, for a satisfactory disposal of the slack, and to prevent pinching the conductor between the unit and the back of the box. This improvement will be of great value in the future development of the socket-outlet ring circuit, where the number of conductors to be so disposed will frequently be six 7/·029's.

The industry has been pressing lamp makers for years to make lamp-caps of an all-insulated material, but so far nothing has been done. I believe that if there is a sufficient demand for insulated lamp-caps the manufacturers will produce them.

In Section 6.1.5, the author says that thermostats are often enclosed in cases of insulating material which, although made for conduit entry, make earth continuity a difficult problem; he adds that metal boxes are therefore preferred. For electrical continuity, a metal box behind the thermostat may be essential, but there is no need to enclose the thermostat in a metal case. Comprehensive earthing is not necessary; for we have not achieved safety through earthing. The proper course, particularly with the advent of plastics, is to develop as far as possible on all-insulated systems, and to ask for metal-cased thermostats is retrogressive, not progressive.

Mr. J. B. Tucker: In referring to "fixing centres" on tumbler-switches the author must have confused some of the dimensional data. The expression "fixing centres" is used by some people, quite correctly, to describe the distance between two fixing holes in the base, and by others to refer to the distance between the centres of actual switches. The statement that there may be a variation from $1\frac{5}{8}$ in to $2\frac{1}{16}$ in seems to be a mixture of the two, because $1\frac{5}{8}$ in is a very general dimension for the pitch of fixing screws through the base, and $2\frac{1}{16}$ in is a fairly general dimension for the pitch between switches. The real position is that $1\frac{5}{8}$ in to $1\frac{11}{16}$ in, a variation of $\frac{1}{16}$ in only, covers the almost universal variation of pitch between the switch fixing screws. I know no switch with fixing screws at a pitch anywhere near $2\frac{1}{16}$ in. On switches a high degree of unofficial standardization is already operating. The dimension of $2\frac{1}{16}$ in obviously refers to the distance between the switches themselves. The great majority, however, are fixed at a pitch of $2\frac{1}{4}$ in. Out of my list of 14 firms, 10 do actually standardize on $2\frac{1}{4}$ in; one uses $2\frac{1}{16}$ in, one firm will supply either, and only two have standardized on 2 in.

With regard to the flat-pin plug, I must challenge the author's suggestion that its use in the U.S.A. and on the Continent is evidence of its merits. It just happened that the United States started with flat pins, as we did with round ones. On the Continent, round pins and not flat ones are almost the universal standard. In countries using the V.D.E. standards round pins are called for, and this applies also to Swiss, Scandinavian and French standards.

In Section 5.6, the author questions the ability of current 5-amp switches to carry 5 amp, but from his next sentence it appears he is really concerned with the breaking, and not the carrying, capacity. Ability to carry even 10 amp on present-day switches is so widely recognized that in several export markets 5-amp switches are permitted to be used for 10 amp, and are marked accordingly.

The B.S.I. Committees which meet from time to time to standardize various matters on request, consist of representative users and makers. Specifications, after being prepared by them, are submitted to all interested parties before final approval, so that none other than users and makers are to blame for any alleged unsatisfactory state of affairs. The features mentioned by the author, such as plug terminals, lampholder terminals, thickness of wall, threads and so on, have been approved by users in committee and by other users before publication. Moreover, the very essence of B.S. specifications for accessories has always been standardization of features giving essential interchangeability, taking care to avoid limitations in design.

Mr. S. W. Melsom: In Section 3.4, the author complains that the colours of the cores of paper-insulated cables have not been standardized. The difficulty in the past has been that engineers generally seem to be unable to agree on one definite colour scheme, probably because the B.S.I. colour scheme for switchboards requires different colours for different types of supply systems and since it is impossible to include all of these types in a cable, especially as some may vary with a slight change in the arrangements of the supply system. The question of colour has given considerable trouble for many years. Although there is a B.S.I. colour code, actually something like 30 different colour codes are in use. The difficulty for paper cables has been surmounted by omitting the colours and numbering the cores; this method is now standardized in B.S.480. This allows the cable maker to make a standard cable and leaves each authority free to choose which numbers should be correlated with its own system of colours. This is the best solution up to the present, but if a simple and universally adopted standard colour code could be devised, there is no reason why mains cables should not be changed back to it.

The author mentions lack of collaboration in connection with the sizes of cables and the entry for them into boxes to which they are connected. This suggestion of collaboration is to my mind most valuable, and there seems to be no reason why it should not be implemented by way of discussions between cable manufacturers, box manufacturers and users.

In his discussion of wiring systems the author refers to pieces of spelter left inside brazed light-gauge conduit—a matter of particular importance since most advocates of this light-gauge tube hold that, on account of its larger internal diameter, it should be allowed to hold more cables. I should like to know whether the author finds that the lumps of spelter are free or if they form a blob on the inside of the tube, in which case they must reduce the size of the conduit available for drawing-in wires. I take it that Sherardizing would not overcome this particular difficulty.

Mr. Cash has mentioned the copper tube system and referred to the advantages of an all-insulated system. I agree with him. In my view, iron pipes are only used for wiring because iron pipes were used in the past for gas. I should like to see a reconsideration of the whole matter with the electrical industry losing its gas-industry complex. Enclosure by iron pipes is probably very good from the point of view of fire protection, but it has been shown in other directions that there is the utmost difficulty, unless the workmanship is very good indeed, in installing a conduit system embedded in plaster or concrete in which the joints will remain permanently at a sufficiently low resistance to deal with any fault current. If these joints are not well made and there is a fault in the cable, it is quite likely that the fire due to arcing at the bad joints will be infinitely greater than with wood casing or unprotected systems.

Mr. F. C. Fuke: In Section 2.3 the author mentions lack of wiring space in air-break switches. I think that this is due to cutting selling prices, and the tendency of a large section of the industry to buy the lowest-price article. The only remedy is for the B.S.I. to prepare a specification stipulating the minimum radius of bend permitted for each size and type of cable, and to issue an addendum slip to each appropriate existing specification calling attention to the new specification. This would put all the manufacturers on the same level.

When steel conduit is screwed into small switch boxes much trouble is caused by the ends of the conduit being screwed out of square; this makes it difficult to get the cover-plate square with the wall. I should like the author's opinion on the method of using a clearance hole in the wall of the switch-box, slipping the conduit through it, screwing the brass bush on the inside of the box and the usual lock-nut on the outside of the box, so that the bush and the lock-nut clamp the wall of the box between them.

In Section 4.6 the author refers to mineral-insulated wiring systems. In my experience of many years ago, the end of the mineral insulation had to be removed before use with a special tool driven down over the inner conductor into the outer conductor and scraping out the mineral between the two conductors. The space between the two conductors was then sealed with a bitumen compound. Has there been any improvement on that method?

With regard to sub-fuseboards, I have suggested that a specification is needed covering the radii of cable bends. Up to a certain weight, only three fixing screws are needed on these boards. Our feet are useless as the surface is rarely flat and one foot is surely touching, so that the whole unit is under stress all the time it is in service. I think three feet and screws are the right number, and suggest that they should be in the form of a triangle. The top screw and the two bottom screws should be at brick-centres, wherever possible.

Regarding porcelain fuses, I endorse the author's recommendations in Section 5.3, but I do not understand his last paragraph. It seems to me that only the manufacturer of the fuse unit can correctly stipulate the size of the fuse wire to be used with it. I suggest that the fuse unit should be indelibly marked by the manufacturer with the sizes of fuse wire to be used for its current ratings. It is not generally known that intermediate-type switches are fully only capable of breaking 1 amp, as the makers, with much ingenuity, have put a comparatively complicated job into the space normally occupied by a single-pole switch. I think that the reason they are regarded as 5-amp switches is that they are mounted on a 5-amp size base, some of which are marked 5 amp.

I do not share the author's hopes, in Section 5.8, regarding the flat-pin type of plug. I find that the flat pin gives more trouble than the round pin, principally owing to the tendency for the flat pin to bend in service. Some types of flat pin will not stand straightening, being of rather brittle metal. There is nothing the flat pin can do which the round pin cannot. I am convinced that the good-quality round-pin plug is the better proposition, and that the resilient contacting feature should be incorporated in the plug-pin so as to rid the socket of complications. In addition to giving efficient and lasting contact, this type of plug eliminates the physical effort usually required during plug insertion and withdrawal, which is proof that the design is not sensitive to the unavoidable errors which occur in bulk production.

Mr. J. I. Bernard: Little is now heard of the copper concentric earth-return system mentioned in Section 4.8. According to my own experience it is a very satisfactory wiring system. I thought it had gone entirely out of use, because the fittings became very special and expensive. I think it has more scope to-day, because there is not now so much objection to multiple earthing, which was widespread at one time on the ground of possible interference with communication circuits.

I have never been quite clear about the need for visible earthing on domestic appliances. It is, of course, a common requirement under the Factory Regulations for industrial gear, but what is appropriate in a factory, where skilled men periodically check that the earthing connections are sound, is superfluous for domestic appliances, which are not subject to any official inspection.

In Section 6.1.6, the author points out that electric fires would be more reliable with a separate connection box. On many of the best makes this is provided, but not on the cheaper ones, probably from cost considerations. The author suggests that a reverse plug-and-socket should be provided with a flexible connection; this agrees with the suggestion made by Mr. Forbes Jackson that every component which could go wrong should be easily detachable by the user for taking to a workshop for rewiring and repair.

With regard to rural installations, I disagree with the author that farm workers are heavy-handed. Also I think that totally-enclosed or even dustproof motors are not necessary as the author suggests. Conditions on a farm or in a barn are not nearly so dusty as in many flour mills and other places where motors operate with very great reliability. I do not think that a standard specification for agricultural motors is required; the ordinary industrial type of motor is quite suitable, as the experience of farmers has shown.

I support the author's contention that either apparatus should be made so good that it never needs to be repaired, or a good deal more attention should be paid to designing something very simple and with standardized fixing connections, so that replacements can be made at very little cost and perhaps by less skilled labour, by which much of this work may have to be done in the future.

Mr. W. H. Brooks: I agree that the size of cables should be marked on them. After installation, it is very difficult for the maintenance man to make further extensions if he does not know the size of the cable.

Surely manufacturers can design a switch or a switch housing which can be easily removed from the case, without the latter having to be broken up or the switch having to be dismantled.

The manufacturers have been much criticized in the discussion, and I think it is time that official statistics were available to determine just what are the best accessories to make for the convenient and efficient use of electricity.

Regarding the grip conduit system, I do not altogether agree with Mr. Forbes Jackson. From a good deal of experience in the Midlands I have found that it is not just a question of the installation itself. Many installations were put in with the building still in a very wet state, and no account was taken of shrinkage in drying out, which, if the conduits themselves were fixed on the wood joists or other fabric of the building, invariably pulled at the grip joints, and once they were broken or drawn, corrosion set in, and a very high resistance reading was obtained within a short time of putting it into service. As far as costs are concerned, I have records of a screwed conduit system and a grip system on similar buildings which show that the costs of the lug-grip system, taking into account the greater number of accessories and fittings as compared with the screwed conduit, were higher than those of the screwed conduit; labour, not material, is the biggest item.

On ceiling switches the cords are the biggest trouble. Where these were installed for protective purposes the cord broke so often that it was replaced by wire, thus defeating the very purpose for which the switch was put in. I had expected the author to make some comments on the use of ceiling switches, and particularly their introduction into bathrooms. I feel that all accessories that claim to conform to B.S. Specifications should carry the B.S.I. mark, which should be used only under licence. Many difficulties could be avoided if it were illegal to sell accessories other than those of an approved standard.

Mr. F. E. Rowland: I agree with Mr. Bernard that the present-day farm worker is not a Neolithic peasant carrying a flint hammer, and I suggest that he is now, and will be to a greater extent after the war, more conversant with a spanner than with a hammer. Farm workers are accustomed to oil-engines and other machinery which require considerable mechanical aptitude, in comparison with which an electric motor is essentially easy to handle. The author suggests the necessity for a special farm motor. Why should the agricultural industry be burdened with a special design, when there are already so many from which to choose? Standard protected-type machines have been widely used on farms and have given very good service. In certain situations, such as dairies, a totally-enclosed motor is undoubtedly called for, while the cowl-cooled type is very suitable for dusty situations.

The author refers to "watertight fittings" for electric sterilizers and other dairy equipment. I suggest that he may have had in mind "weatherproof fittings," which I am sure he will agree are generally adequate.

Regarding the last paragraph of Section 6.3, I think that it would be almost dishonest to sell an installation with 57·8 volts to earth with an implied suggestion that it was safe, which would certainly not be the case with farm animals. If the voltage were reduced so low that it was safe, it would be impracticable for use. I suggest that so far as cow byres and similar situations are concerned there are two alternatives for absolute safety. One is to ensure that those parts of the building to which the livestock have access cannot possibly become alive, and the other is the leakage trip. In 14 years' experience in this field I can remember only one serious accident to cows in this country, and that would not have occurred if one of these precautions had been taken.

Mr. F. H. Mann: In regard to industrial oil switches, the author says: "these are generally satisfactory, but tank-lowering gear would be appreciated even on the smaller sizes." He seems to forget some undesirable features of certain switchgear, especially of the vertical isolation type. First, it is important that the shutter be designed to act in strict relation to the position of the switch. Secondly, the safety shutters must have provision for locking in position over the spout contacts to prevent access to them, as when cleaning or inserting leads for testing purposes.

Similarly, with a double run of busbars in a casing the contacts should be clearly marked to identify the live from the dead. At least one undertaking has tried to overcome this difficulty by marking the busbars with lines or colours, and extending those to denote the position of the associated contacts within the switch.

On medium-pressure or low-pressure switchgear where the switches or fuse elements are mounted on the busbar and form part of the busbar assembly, it is desirable that an insulating barrier should be interposed between these and the busbars to prevent any tools being dropped into the bars when a man is working on the fuse or switch unit. A number of accidents have been caused by a serious short-circuit being set up in this way.

Portable apparatus is another item which the author describes as satisfactory, but I can scarcely agree with him that such apparatus gets better treatment in factories than in houses. Every year about one-third of the fatal electrical accidents in factories are caused by portable apparatus, the use of which is attended by a special risk because of the certainty of its being handled and the uncertainty of its remaining earthed.

I agree on the need for good cord-grips and on some means, such as a tapered rubber sleeve, to prevent acute bending at the point of outlet; this would remove one of the most prevalent causes of shock and burns. So far as flexible metallic tubing and its connections are concerned, it may be difficult to find satisfactory connectors and resort has therefore to be had to soldering or brazing, which is dangerous if done with the cables inside. There is, or was, a suitable connector available in the form of a split coupling, screwed inside, in which the flexible is placed and then clamped down. This gave excellent continuity, and also a neat termination for the end of the flexible metallic tubing.

Mr. P. S. Cattle: Motor-starters mentioned in Section 2.1 are often enclosed in an iron case, and access to them with conduit is probably limited to the bottom only; to get at any terminals or to tighten up connections at the back of the panel is not easy, owing to the depth of the iron case. Starters should be made so that full access is obtainable by removal of the outer case.

Switch-fuses should be reversible, so that they can be used with supply cables entering the switch either at the top or bottom, without the cables passing by the fuses. I agree on the need for replacing damaged units. It has been the custom of certain makers to fix their porcelain units on the back of the switch-case with small nuts, which are not accessible and which slacken with use. Porcelain bases should be fixed on to metal strips by set-screws with cushioning washers, or the whole of the switch-and-fuse gear carried on a separate frame inside the casing. Terminal connections should be easy of access; where a sweating thimble is used, a set-screw fixing, instead of passing the thimble over a stud, makes a better job.

We have had considerable experience with bird-cage wiring on armoured cable, but have not found the tape satisfactory. We use a heavy oval galvanized-wire wound in the reverse direction. The tape has a cutting edge which holds itself in one position on the galvanized wire, and when pulling the cable round a given radius the tension is sufficient to break the mild-steel tape. For unarmoured cables it is suggested that the lead sheath should have a small fin or fins to indicate the number of cores in the cable, and flats on this fin to indicate the size of the conductor. Our chief difficulty with the colouring of v.i.r. cables is bad delivery of cables of the yellow and blue varieties. Cable makers do not carry any great stocks.

In Section 4.1 the author recommends a brass washer. For some years we have used a lead washer against a faced socket, with very good results. The lead washer is placed outside the box, with a good-class socket bush (not one with skimped metal) inside the box.

I should like to have a few standard designs for porcelain

fuses. So many different types of fuse are now offered that it is often difficult to replace them when broken. They should be suitable for h.r.c. or ordinary fuse wire, with substantial contacts. At present we get copper, phosphor-bronze, stamped, cast, fixed and self-aligning contacts. In a recent job, 800 switch-fuses, all of the same design, were wanted over a period of two or three years; from one maker we got three designs of switch with different fixing-holes, different centres and different sized castings.

We have tried to use small circuit-breakers, but found that they fail after about 15 000 operations at maximum load on inductive circuits. Some tumbler-switches with phosphor-bronze contacts have done 200 000 operations. The modern porcelain bases are often very thin, and bases crack owing to lack of strength and because terminals or fixing screw holes are placed too close to the outer walls.

Mr. R. Marryat: The first object of the maintenance engineer when dealing with industrial equipment is to foresee and prevent breakdown, and, to make this possible, simple means of access to all parts which have to be inspected or adjusted must be provided. This point is sometimes overlooked in totally-enclosed control gear and motors. I should like to see all automatic controllers fitted with interlocked isolating switches and provided with glass inspection panels, so that the maintenance engineer can watch the operation of the controller. Provision should be made in all enclosed motors for fitting feelers between the rotor and the stator to determine when bearings need attention.

The second object of the maintenance engineer is to cut down the length of any stoppage to the shortest possible time, and I endorse the author's plea for standardization. If motors and other equipment were standardized so that a new motor could be installed without having to alter fixings, wiring connections and so on, very much time and trouble would be saved. The third object of the maintenance engineer is to carry out necessary repairs at minimum cost. Many motor and starter repairs can be carried out more effectively in the workshop than on site, and costs can often be reduced by fitting a replacement unit whilst repairs are carried out. Here again standardization would help.

I am pleased that the author advocates a standard position for terminal blocks on motors, and I support his view that all terminal boxes should be of the rotating type.

Mr. W. Cross (*communicated*): The author has pointed out certain faults in electrical equipment which are well known to those who fix and maintain them, but are often ignored by manufacturers; it would be an advantage if designers would pay attention to these points and seek guidance and advice from those with experience of fixing and maintenance work.

I do not favour exposed earths, which are often tampered with; if the earth connections were in terminal boxes or connectors they could be easily inspected by the maintenance staff.

I do not think the author's suggestion for a flexless iron would be popular with the users. To carry the flexible cord away from the iron a spring can be fixed to the flexible about four feet from the iron, with the other end of the spring attached to the wall about four feet above the table.

Mr. E. N. Evans (*communicated*): While I endorse almost all of the views expressed in the paper, there are a few further recommendations which would help towards ease of maintenance.

If a simple device could be incorporated in motor starters to open all three phases of an a.c. supply should one phase fail, burn-outs due to single-phasing would be avoided. With most designs it is almost impossible to gain access to the back of a wall-mounting panel without dismantling the starter; a panel which would withdraw on rails, or hinged brackets on the starter mounting, would partly overcome this difficulty. Isolating switches should be interlocked with doors or covers, and provision made for the isolator to be locked in the off position, the key being held by the person who would be endangered should the power be restored. Circuit diagrams should be cast in the lid so as to be always available for inspection.

On industrial oil switches a simple yet valuable help would be the fitting of inlet and outlet valves suitable for attachment of oil-reconditioning apparatus, allowing oil to be cleaned while under load.

On main distribution boards, at least one manufacturer extends connections to fuses by copper rod to special easy wire terminal boxes situated either at the top or the bottom of the distribution board; this feature could well be standardized.

In h.r.c. fuses, the indication of blown fuses is a time-saving device which should be incorporated in new designs.

Considerable improvement could be effected in the wiring arrangement of fluorescent fittings, present practice of some manufacturers in using twisted art-silk flex for inter-lampholder wiring leaving much to be desired.

Earthing arrangements on portable hand-lamps require attention. I do not know of one of the insulated variety in which any provision is made for earthing the wire lamp-guard. If a lamp is broken the filament standards remain charged and often make contact with the wire guard, so raising it to a dangerous potential above earth.

Most electric cookers require improved heat insulation, some being more space heaters than cookers. Access to fuses should be from the front rather than the side, particularly in view of the built-in feature, which is gaining popularity and would no doubt be standardized in pre-fabricated homes.

On motors and generators, terminal boxes should be duplicated, one on each side of the machine, to remove the necessity of the large unsupported bend of cable often present with top-mounted terminal boxes. Screwed air-gap plugs seem to be called for in totally-enclosed machines, the correct air-gap measurement being stamped on the motor end-plate above the hole.

Mr. W. S. Hunt (*communicated*): I think it is generally agreed that, to reduce maintenance costs, care should be taken in the first place in the selection of each individual piece of apparatus, bearing in mind the nature of its functions and the conditions under which it has to operate. Apparatus and plant considered unsatisfactory from the maintenance point of view would normally find no market, and the manufacturer would be left with the alternative of withdrawing it or making an improvement. As a rule, maintenance engineers are accustomed to overcome weak points in design and frequently carry out alterations of a minor character on site, to reduce the time taken up by periodical inspections and routine maintenance, and to reduce the likelihood of accidents.

Starters, switches and control gear generally, are too frequently mounted in awkward positions without any regard to convenience of inspection and adjustment. Isolating switches are incorporated in motor starters by all good manufacturers to-day, except perhaps in the smaller sizes where the cost of a separate switch would be prohibitive.

Inspection of the wiring in war-damaged buildings should give some interesting information as to the best type of conduit to use, at least from the point of view of continuity. Joints which have pulled out through insufficient threading or through not having been gripped sufficiently would indicate whether the material or the workmanship was at fault.

I have seen porcelain fuse carriers on which the fuse wire is clamped under a non-rotating plate washer; the wire is cut long enough to pass under and then bend back over the plate. This eliminates the stretching and possible breaking of the fuse wire whilst being clamped. Such a clamp could be used in plug tops, the strands of the cable being spread out before being passed under the plate washer. This method of connecting cable ends is adopted in certain small types of starters.

In industrial plant there surely should be no necessity to use lubricating oil to the extent suggested in the paper, since, except perhaps with fractional-h.p. motors, ball and roller bearings seem to have been universally adopted for some years. In fractional h.p. motors, where oil-soaked pads are used, the amount of oil required is so small that unless more lubricant than is necessary has been applied, no inconvenience from oil creeping should arise.

In the larger types of motors and generators, some features which I think could usefully be improved to facilitate stripping down for the purpose of replacing bearings, turning slip-rings and commutators and similar work, are: (*a*) the method of mounting the bearings; (*b*) the method of connecting overhung or outer slip-rings to their rotor loads; (*c*) the varieties of fit applied to couplings and their shafts, with special reference to the facilities for drawing off and replacing couplings without having to resort to heavy presses, and (*d*) the type of key used.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. H. Drake (*in reply*): It is impossible in the space available to reply to the numerous comments which have been made on the paper, and I must therefore confine myself to the constructive proposals which may be of value to the industry.

Mr. Forbes Jackson suggests that the E.C.A. should draw up a list of approved apparatus, while Mr. Brooks favours licensing by the B.S.I., but I do not think that either of these suggestions will entirely meet the case. As long as there is severe competition in the industry some contractors will always buy at the cheapest rates, and it is essential therefore that a higher minimum standard should be fixed on the basis of operational experience. Requirements, such as that suggested by Mr. Fuke, namely that in all apparatus provision must be made for a minimum radius of bend for each size and type of cable, would be a step in the right direction. No doubt other basic principles could also be enunciated on the same lines.

There will always be disagreement over the question of grip fittings, and whereas Mr. Forbes Jackson's experience has been satisfactory, there is much to be said for the view expressed by Mr. Brooks. Many installation engineers are afraid of using the grip system because of its inherent disadvantages, for if for some reason it is disturbed there is undoubtedly the danger of loss of continuity.

Mr. Forbes Jackson's suggestion with regard to the provision of larger boxes and the use of tails to connect accessories is ingenious and has many advantages. The initial cost should not be excessive, and if it became recognized as good practice, or better still obligatory, all parties would benefit.

The general support for a newly designed plug for use with the proposed ring-main circuits to be used in post-war housing is interesting. It seems clear that the suggestion to up-rate the existing 5-amp plug could only result in chaos, quite apart from the fact that there would be insufficient space to admit the looping of the ring main in the existing standard terminals.

The mechanical protection for t.r.s., to which I referred, was of course only in positions, such as switch drops, where it would be liable to mechanical damage.

I am, of course, in entire agreement with Mr. Cash that an all-insulated system is the ideal at which to aim, but so long as this ideal remains incapable of attainment it is surely necessary to do the next best thing and make it possible to provide adequate earthing.

Mr. Tucker points out an error in my remarks about fixing centres on switches, and I should like to thank him for doing so. On further investigation I find that his statements are correct. It is also true to say that my remarks referred to the breaking capacity of switches and not to their carrying capacity, but the function of a switch is to break current, and if it will not do this adequately the fact that it will carry the current seems to be of little value.

The question of flat-pin plugs has been discussed so often that it would be fruitless to enter into further discussion as to their merits or demerits. That they can be produced cheaply and that they function efficiently in America is beyond question, but round-pin plugs designed on the lines suggested by Mr. Fuke have many advantages and certainly look better and are more robust than many existing types of flat-pin plugs. It is difficult to see how the use of a bush and lock-nut, to which he also referred, would assist matters when connecting screwed steel conduit to small switch-boxes. The alignment then would depend on the angle of the face to which the bush and lock-nut were screwed up, and this might be just as likely to be out of line as the thread used in normal practice to-day.

Mr. Fuke makes many other useful suggestions; that referring to the fixing centres for fuseboards would appear to be practical and effective. His remarks about intermediate switches being rated considerably below 5 amp, although the base upon which they are mounted is marked for this current, are interesting and not generally appreciated; as much publicity as possible should be given to this potential weakness.

It is very heartening that multiple earthing and the use of single-line concentric wiring receive the backing of Mr. Bernard, but I still cannot agree with him or Mr. Rowlands with regard to agricultural equipment. Having had considerable experience as a practical farmer and as a member of the N.F.U., and having carried out many farm installations, I am quite satisfied that no such installation, at any rate in this generation, will receive sufficient care or maintenance. The farmer and his workers lack time, and anything which continues to operate is ignored until it goes wrong, when emergency repairs of the crudest kind are usually resorted to. I still maintain, therefore, that extremely robust apparatus is essential.

Mr. Mann's criticisms of industrial switchgear and portable apparatus deal more with the safety factor than with maintenance, and in view of this these points were omitted from the paper, which was intended to deal primarily with maintenance. The split connector which he recommends for flexible metallic tubing meets the difficulty adequately and should become standard practice.

Mr. Cattle makes a number of very valuable suggestions which will, I hope, lead to improvements in the design of electrical equipment.

Finally, I should like to endorse very strongly Mr. Hunt's plea that *good* apparatus should be installed. Experience has shown that it is cheapest in the end, and there is no doubt whatever that increased measures of standardization will assist maintenance engineers more than any other single factor. Designers should make up their minds whether any individual piece of apparatus is to be replaced *in toto* if trouble develops, or whether faulty parts only shall be renewed. In the first case the cheapest, simplest, and most robust design is called for, and no provision should be made for repair. In the second case easy replacement and maintenance must be first considerations. Designers are too apt to forget this fundamental distinction and to produce apparatus which is neither cheap to replace nor sufficiently robust to avoid trouble, and yet so designed that replacements are major operations. So much of the apparatus now on the market is already good that it should not entail much effort to improve the remainder, and it is hoped that the paper and discussion may provide the necessary stimulus.

REINFORCED-CONCRETE TRANSMISSION LINE SUPPORTS*

By E. C. NEATE, B.Sc.(Eng.), Member,† and W. F. BOWLING, Associate.†

(*The paper was first received 28th October, and in revised form 6th December*, 1943. *It was read before the* TRANSMISSION SECTION *8th March*, 1944.)

SUMMARY

The paper, after briefly considering previous work done in Great Britain, discusses the requirements of a reinforced-concrete transmission-line pole.

Details are given of experimental poles, with an analysis of results of tests to destruction. A graphical method of design is developed and sufficient information is provided to enable future work to be undertaken on the bases established. An expression is obtained for the deflection of a pole under load, and it is shown that deflection cannot be taken as a criterion for proof-test purposes.

Fabrication and erection methods are discussed, and the paper concludes with a survey of the advantages and disadvantages of the concrete pole, reference being made to a questionnaire issued to a number of users in this country.

(1) INTRODUCTION

The types of transmission-line support available are:—

(*a*) Wood poles.
(*b*) Steel tubular poles.
(*c*) Reinforced-concrete poles.
(*d*) Lattice-steel structures, either of rigid or flexible type.
(*e*) Poles of the steel-girder type, either simple or composite in form.

Under war conditions, the restrictions imposed by difficulties of manufacture in this country and of importing from abroad make all types of support more difficult to obtain. The decision as to which type should be used is affected to the extent that economic questions become less important in relation to availability of supply.

The most common form of support in peace time is the imported red fir pole (*Pinus Sylvestris*). Larch and other home-grown poles have been made available in reasonable quantity, but it is unfortunate that the experience with this type of pole erected during the last war has been bad, and it would appear possible that this experience will be repeated. It seemed obvious that, for lines which will continue as part of a network after the war, consideration should be given to other alternatives that are available. The present paper deals with some of the types of concrete poles that have been developed.

(2) GENERAL CONSIDERATIONS

(2.1) Previous Work

Concrete poles had been in use for many years prior to the outbreak of war. They may be divided into two classes, the spun type in which the pole is cast centrifugally in a machine, and the hand-moulded type in which conventional concrete practice is followed. The former mode of manufacture is common on the Continent, but has met with little favour in this country. Due to the method of casting, the pole is usually, but not necessarily, circular in section, equally strong in all directions, and tends to be heavy as compared with the hand-moulded type. An example of a transmission line constructed with spun poles is the C.E.B. line between Worthing and Brighton. The cost of the special plant is high, and a demand has not yet developed which justifies the installation of equipment at various centres in the country.

The alternative hand-moulded pole has been erected in fair numbers in this country during the past 12 years. The designs generally adopted appear to have been based upon Continental practice and to have given satisfaction, although reference has been made by Eve to difficulties due to spalling which has occurred.[1] On the Continent this type competes with the centrifugally-cast pole and is widely used. Under war-time conditions it offers advantages over the machine-made pole, since very little special equipment is required.

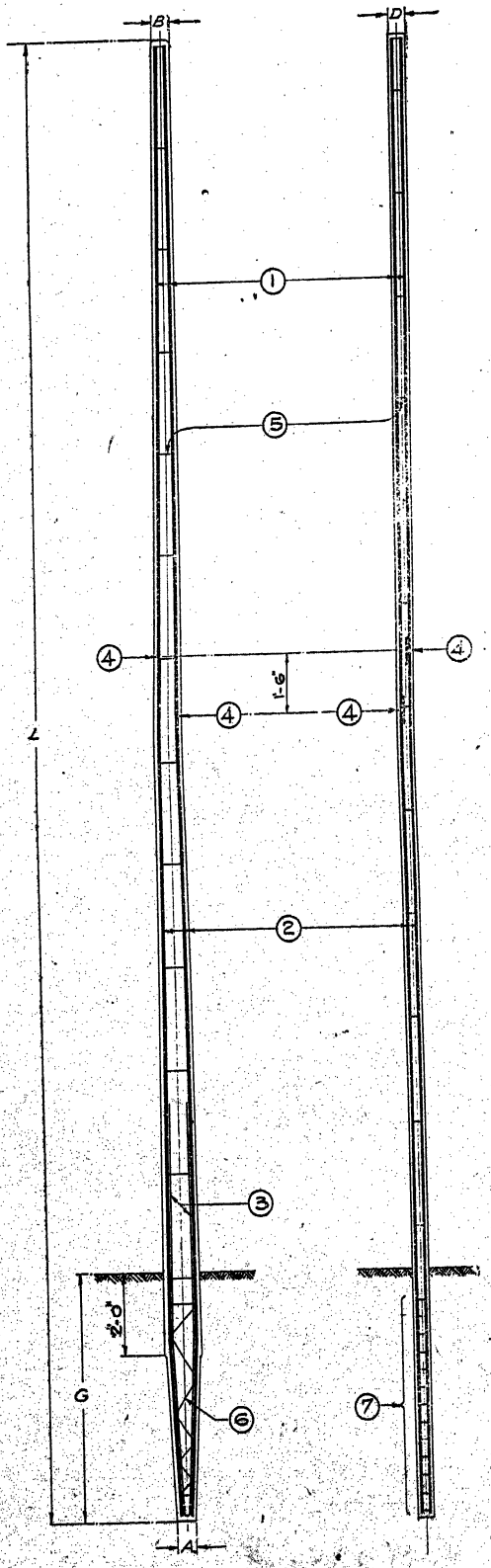
It is surprising to note that, compared with the small total length of overhead lines constructed with reinforced-concrete poles in this country, a considerable volume of research work connected with their fabrication and use has already been carried out. In 1933, at the instance of the Electricity Commission, the E.R.A. published a paper by Morgan.[2] This dealt with the practice as then established, and B.S. 607—1935, issued shortly afterwards, embodied certain of the recommendations made. The primary object of this investigation was to examine the possibility of a relaxation in the factor of safety specified in official regulations, and the conclusion reached was that, given adequate control during manufacture, a reduction of the factor of safety from 3·5 to 2·5 should be permitted, except at crossings, for which a figure of 3·0 was recommended. In practice the Electricity Commission now permit a factor of safety of 2·5 for all supports, once approval has been given to the design and mode of manufacture.

(2.2) Present Designs

The design of reinforced-concrete poles, whilst not difficult, presents problems which do not occur in the case of the reinforced-concrete structures, since, for the latter, the maximum working stresses are usually specified by the building authority, and the designer is required to satisfy the authority that these maximum stresses are not exceeded in the various members of the structure under definite specified loadings. A structure then results which should give a useful life without failure under the most severe loading and weather conditions which it is estimated it will be called upon to withstand. The design of supports, on the other hand, is controlled by the Electricity Commissioners' Regulations, which specify that transmission lines shall be capable of withstanding a defined ultimate load based upon the maximum working conditions multiplied by the factor of safety approved. These regulations specify the ice and wind loadings to be assumed acting on the support transverse to the line, and require that in the direction of the line the support shall not have less than one-quarter of this strength. Furthermore, it is laid down that the design must be accompanied by a complete set of calculations for approval, or that a pole shall have been tested to demonstrate that it will meet the required ultimate load. The former method has not in the past been altogether satisfactory, since experimental data have not yet, in ordinary practice, been correlated with design figures under conditions of ultimate loading. It will be seen, therefore, that the design problem is to determine the conditions under which the pole will fail, and is thus quite different in its nature from the requirements of normal structural engineering. Even the meaning of "failure" is not satisfactorily defined at the present time. Morgan[2] has proposed that "failure" should

* Transmission Section paper.

† Riley and Neate, Ltd.



PARTICULARS OF CLASS "B" POLES

Ultimate transverse load at 2 ft from top — 1 250 lb.

Length of pole, ft (*L*)		28	30	32	34	36	40
Depth in ground, ft (*G*)		5	5	6	6	6	7
Breadth at top of pole, in (*B*)		4⅛					
Taper—transverse face, in/ft		1/6					
Depth at top of pole, in (*D*)		4⅛					
Taper of longitudinal face		No taper					
Breadth at butt of pole, in (*A*)		5					
Main reinforcing rods (1)–(2)		4, ⅞ in dia. high-tensile steel; no joints					
Auxiliary reinforcing	(3)	Not required					
Bracing above ground	(5)	¼ in dia. mild-steel rods spaced 2 ft 6 in					
Bracing below ground	(6)	2, ½ in dia. mild-steel rods					
	(7)	¼ in dia. mild-steel rods spaced 5 in					
Weight of steelwork, cwt		2¼	2½	2¾	2¾	2¾	3¼
Total weight of pole, cwt		10½	11½	12.	12½	13½	16½

PARTICULARS OF CLASS "D" POLES

Ultimate transverse load at 2 ft from top — 2 500 lb.

Length of pole, ft (*L*)			32	34	36	40	45	50
Depth in ground, ft (*G*)			6	6	6	7	8	8
Breadth at top of pole, in (*B*)			5½					
Taper—transverse face, in/ft			1/6					
Depth at top of pole, in (*D*)			4⅛					
Taper of longitudinal face, in/10 ft			1/6					
Breadth at butt of pole in (*A*)			6					
Main high-tensile steel reinforcing rods	(1)	Length, max.	No joints required			19' 9"	19' 9"	19' 9"
		Dia. in				1	1	1
	(2)	Length, min.	Rods:—1⅛ in dia.			20' 0"	25' 0"	30' 0"
		Dia., in				1⅛	1⅛	1⅛
Auxiliary high-tensile reinforcing rods	(3)	Length, min.	Not required				10' 0"	15' 0"
		Dia., in					⅝	⅝
Joints	(4)		No joints required			⅞ in dia. × 8 in high-tensile rod welded to main rods		
Bracing above ground	(5)		¼ in dia. mild-steel rods spaced 2 ft 6 in					
Bracing below ground	(6)		2, ⅞ in dia. high-tensile steel rods					
	(7)		¼ in dia. mild-steel rods spaced 5 in					
Weight of steelwork, cwt			4	4½	4½	4⅞	5½	6½
Total weight of pole, cwt			15½	17	18½	21½	25½	30½

Fig. 2.—Class "B" and Class "D" poles.

mical arrangements, particularly when a small increase in height requires the substitution of a larger rod. To a considerable degree the steel areas available are controlled by these fixed diameters, although it is possible to fit additional small rods alongside the main rods to give a small increase in steel area when required.

For convenience in manufacture it was thought preferable to have a complete range of poles of a particular class made in one standard shape of mould. The moulds are generally arranged to taper both in the transverse and longitudinal directions, the taper being suitable for use with poles up to a maximum length determined largely by handling facilities and line requirements.

When the preparation of the first range of designs was commenced, the dimensions at ground level of the most frequently used height were fixed to give the required resisting moment corresponding to the class loading. The dimensions at the top of the pole were then chosen, such that with a suitable taper the section at the butt of the maximum length of pole, which was assumed to be 55 ft, would not be excessive. In fixing the top dimensions of the pole some consideration was also given to the maintenance of sufficient strength for local bending when the pole was stayed at a level below the pole top. By suitable adjustment of the size of reinforcing rods, a pole was developed which was not too unwieldy in the longer lengths and which, at the same time, was economical throughout the range. A similar consideration fixed the dimensions of the pole in the longitudinal direction.

(3.1.2) **Cost of Manufacture.**

The manufacturing costs comprise:—

(*a*) Standing charges.
(*b*) Sand and ballast.
(*c*) Cement.
(*d*) Steel.
(*e*) Labour, including supervision.

Of these the first three are relatively unimportant, whilst the fourth and fifth are responsible, under present conditions, for approximately 75% to 85% of the total cost of the pole. In order to keep labour costs low the forms used for casting should be of the simplest type possible, and easy to clean and assemble; the steel reinforcing frame should be fabricated to jigs and should also be as simple as is consonant with the requirements of design. The scheme of corings for pole steelwork is required to be adaptable to the majority of poles needed, and special corings should be avoided. The poles should be mechanically handled and loaded, and the handling of reinforcing frames, which may themselves be of considerable weight, should also be reduced to a minimum by fabricating the frames close to the casting floor which, in turn, should be adjacent to the curing bays.

The reinforced-concrete pole, being considerably heavier than the wood pole it is designed to replace, usually requires special erection methods. Thus the cost of manufacture is not the sole consideration, the lowest possible cost of the erected transmission line being the final objective. Experience has proved that when an economic balance is struck between the labour required in producing the pole, including its raw materials, and the cost of handling and erection, more favourable results have been obtained when a judicious increase in the fabrication cost has been allowed. Later designs have resulted in a saving in form work, and labour costs in producing the steel frame, which so counterbalanced the cost of the additional steel required, that reductions in manufacturing costs of 20% and field erection cost of 10% were achieved.

(3.1.3) **Durability.**

The chief factors governing the life of a concrete pole are (*a*) the ability of the concrete to retain its strength, and (*b*) the protection of the steel reinforcement from corrosion. The quality of the concrete, its method of mixing, placing and curing, and the subsequent handling of the pole before erection are therefore of great importance in determining the durability of the finished pole.

The quality of concrete required can be specified as regards the proportions and quality of cement, sand, gravel and water to give a material that has sufficient strength to meet the design requirements, but it is essential that the workmen fabricating the poles should be under strict supervision to ensure that the specified requirements are strictly worked to. This is particularly important as regards the amount of water used; this has an important bearing on both the strength and porosity of the resulting concrete.

The strength of concrete is greatly increased by keeping the water/cement ratio to a minimum consistent with a workable mix. Any water added in excess of that required by the cement to complete the chemical action results in a poorer-quality material, since the surplus water, on drying out, leaves minute voids in the concrete, so causing a reduction in strength and an increase in porosity with a corresponding loss of durability. If a dry mix is used it is difficult to ensure that the concrete will be well tamped around the steel frame if done by hand, and the use of mechanical vibrators has greatly simplified this problem. In using mechanical vibration it has been found that when placing the concrete, a mix having a water/cement ratio (by weight) as low as 0·45 can be used satisfactorily even under the most difficult conditions. The amount of concrete cover for the reinforcing rods is fixed by the size of the aggregate used. It should be such as to allow the free passage of the concrete between the mould and the steel bars during placing, with a minimum value to ensure adequate protection of the steelwork under erection and service conditions. If, during placing of the concrete, the steel reinforcing frame becomes displaced, there is a danger of the specified cover being reduced, resulting in the possibility of damage during subsequent handling and erection of the pole.

The life of a concrete pole is dependent upon the steelwork being protected by the concrete from the effects of moisture and chemicals in the atmosphere and in the ground. Any cracks which may develop owing to handling, and which are sufficiently open to prevent autogenous healing, will have a detrimental effect. Some care is therefore necessary during handling, whilst both the duration and conditions of curing have an important bearing on the durability of the pole.

(3.1.4) **Appearance.**

A reinforced-concrete building can usually be designed to appear lighter and more graceful than the corresponding brick structure which it substitutes. The reinforced-concrete pole, on the other hand, is required in place of a wood pole which is inherently lighter than the concrete pole. There is a tendency for the concrete pole to appear clumsy by comparison, and a consequent need for an appearance of lightness combined with strength. With this object in view the first designs were prepared having an I-section, with moulded flutings and corings. Since a diagonal system of bracing was used to carry shear, corings to reduce weight could approximate only to triangular prisms. In the interests of appearance it was decided to make the corings semicircular, and a central fluting on either side of the pole was added to produce an effect of lightness and to break the harshness of the lines. The resulting pole had an appearance which was satisfying without appearing clumsy, and if pigment had been available for use in the concrete, the pole would have blended well with the countryside.

Table 1

Pole serial number	4	5	6	7
Date of manufacture	29.2.40	5.3.40	11.3.40	13.3.40
Main reinforcing bars (high-tensile steel to B.S. 548—1934)	6—$\frac{7}{8}$in dia.	6—$\frac{7}{8}$in dia.	6—$\frac{3}{4}$in dia.	6—$\frac{3}{4}$in dia.
Method of connecting bracing to main rods	Bound	Welded	We'ded	We'ded
Cement used	"Ferrocrete"		Aluminous	
Fine aggregate	Sharp washed river sand			
Coarse aggregate	$\frac{3}{8}$-in crushed whinstone			
Concrete mix	1 : 1$\frac{3}{4}$: 2$\frac{3}{4}$ (by volume)			
Method of placing	Hand		Vibrated	

Nevertheless, the expense of providing corings and flutings represents a very considerable proportion of the total manufacturing cost of the pole. The forms are intricate and become worn out after a limited number of uses. Experiments have been made with rubber and plaster-of-paris moulding bases in place of hard wood, but insufficient progress has been made to justify a change in the present moulds. With the Class "B" and later Class "D" poles the special mouldings have been omitted and the width and depth of the pole reduced at the same time, retaining an appearance of lightness which has proved a desirable feature in obtaining wayleaves. This solid type of pole has been standardized for future work, except the heavier types of construction.

(3.1.5) **Foundations.**

In addition to the foregoing considerations which affect the design of the pole itself, the question of foundation strength must be considered. For poles up to Class "D" the usual kicking blocks are satisfactory, but above this rating special foundation designs are required. A foundation for the Class "EX" pole was produced and has been satisfactorily tested and used in service.

It is not proposed to deal at length with this subject, since foundation design is outside the scope of the present paper. In general, it is the authors' view that the foundation should fail before the pole, thus resulting in the least possible damage to the transmission line as a whole. This is particularly important in the longitudinal direction of the line, where loads due to conductor failures may be applied. The longitudinal flexibility of the concrete pole is advantageous in assisting the foundation to produce equalization of loads in the adjacent spans after failure.

(3.2) Basic Designs

As mentioned in Section 2.2, the first poles fabricated were of an experimental nature. The basic design was for a 36-ft pole and the method used was similar to that for a reinforced-concrete beam having steel on both the tension and compression sides of the neutral axis.

A number of calculations were made, using various sizes of reinforcing bars, the section of the pole being adjusted to give the required resisting moment corresponding to the loading. The outline finally decided upon is shown in Fig. 1, the pole being of H-section above ground level, and the web being cored with semicircles in order to reduce the weight and give a pleasing appearance to the pole. Light steel bracing rods were provided to take the shear load. Below ground level the section of the pole was of U-form in order to accommodate the additional bracing required to withstand the heavy local sheat due to ground reactions.

Four poles were manufactured to this basic design for purposes of test. The main particulars are given in Table 1.

(3.3) Tests of Basic Designs

The poles detailed in Table 1 were tested on the 28th March, 1940, in the following manner.

Two poles were securely bolted together between wood baulks over the bottom 6 ft of their length, corresponding to their assumed depth of planting in the ground, the major axis of their section being in the horizontal plane. In order to avoid points of high pressure and to ensure that the reactions over the area in contact should approximately correspond to service conditions, the sides of the pole over the lower 6 ft were covered with thick felt. The test load was applied by pulling the two poles apart at the top, the point of application of the load being 2 ft from the pole top. Deflections were measured by means of theodolites, deflection scales being fitted near the top of the poles.

Poles Nos. 4 and 5 were tested first. Both poles commenced to fail between the clamping baulks at a load of 3 500 lb, the deflection of pole 4 being 18$\frac{1}{4}$ in; at the same load a deflection 17 in was read for pole 5.

Poles 6 and 7 were then tested; they both failed between 5 ft and 7 ft from the butt. The test load when failure occurred was 2 500 lb, the deflection of both poles being 15 in.

(3.4) Analysis of Tests on Basic Designs

The results of tests on the experimental poles were analysed with the object of determining the stresses in the concrete and steel at the point of failure:—

(*a*) By the "steel-beam" theory based on the assumption that the main reinforcing steel acts in a similar manner to the tension

Table 2

Pole serial numbers	Load at failure	Method (*a*)	Method (*b*)		
		Stress in steel	Value of *m*	Stress in steel	Stress in concrete
	lb	tons/in^2		tons/in^2	lb/in^2
4 and 5	3 500	26·10	15	26·4	3 010
			13	26·3	3 300
			11	26·2	3 670
6 and 7	2 500	25·40	15	25·6	2 620
			13	25·6	2 870
			11	25·5	3 150

and compression flanges of a rolled-steel joist. In this method the stress in the concrete is ignored.

(*b*) By normal design methods, allowance being made for the compression in the concrete assisting the steel on the compression side of the neutral axis. For this investigation the value of the modular ratio m was taken as 15, but the stresses in the steel and concrete for modular ratios of 13 and 11 are also given in Table 2, from which it will be seen that the effect on the steel stress of variation in the modular ratio is negligible.

The close agreement obtained for the stress in the steel by the two methods of analysis was noted and an examination was later made as to the limitations of method (*a*) for purposes of rapidly determining the approximate strength of new designs.

The above results show that the steel stress corresponding to the ultimate strength of the pole is approximately 26 tons/in^2, which corresponds to the yield stress of the high-tensile steel used for the main reinforcing rods. Steel manufacturers' test-report sheets give figures slightly in excess of 25 tons/in^2 and this stress has been adopted as a basis for all later designs, producing a slightly conservative design.

(3.5) Derivation of Charts*

The resisting moment given by the "steel-beam" theory is

$$R = f_t \frac{A}{24}(d - 2a) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If allowance is made for the effect of the concrete taking part of the compression the above equation for a rectangular beam becomes

$$R = f_t \frac{A}{24}(d - 2a) - \frac{f_c b x}{24}\left(\frac{x}{3} - a\right) \quad . \quad . \quad . \quad (2)$$

The second term of the right-hand side of this equation is the correction due to the centre of resistance of the concrete not coinciding with the centre of the compression steel. If $x/3$ is equal to a the second term of equation (2) becomes zero and the resisting moment given by the "steel beam" theory is correct, providing the width of the beam is such that the steel and not the concrete stress governs the design.

In the case of the experimental poles, as the value of m is reduced the value of $(x/3 - a)$ approaches zero, thus explaining the closer agreement between the steel stresses for the smaller values of m.

The "steel beam" theory thus gives results that are sufficiently accurate, with poles of normal section, to enable a rapid investigation to be made of new designs, and, using equation (1), curves of resisting moments were plotted for various bar diameters and depth of section. A steel stress of 25 tons/in^2 was assumed with a concrete cover of $\frac{3}{4}$ in as given by B.S. 607—1935.

Whilst the "steel beam" theory gives a useful guide to the bar diameters and depth of section required for a given resisting moment, it is necessary to investigate both the stress in the concrete and also its effect on the lever arm of the resisting moment, before the design can be completed.

The position of the neutral axis relative to the compression face of the concrete x is given by

$$\frac{1}{2}\left(d - \frac{a}{m}\right) = \frac{bx^2}{2mA} + x\left(1 - \frac{1}{2m}\right) \quad . \quad . \quad . \quad (3)$$

This equation makes allowance for the loss of concrete area on the compression side of the neutral axis due to the compression steel. If allowance is not made for this loss of area equation (3) reduces to

$$\frac{d}{2} = \frac{bx^2}{2mA} + x \quad . \quad . \quad . \quad . \quad . \quad (4)$$

* The symbols employed are given in Appendix 9.1.

and the final results obtained by the use of this formula are sufficiently accurate for practical purposes.

Equation (4) can be further reduced to

$$P = \frac{50X}{m\left(\frac{1}{2X} - 1\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

That is, for a given value of the modular ratio and the percentage reinforcement, the value of the neutral axis factor can be determined.

Curves connecting P and X for a modular ratio of 15 are shown in Fig. 3.

The ratio between the tensile stress in the steel and the maximum compressive stress in the concrete is given by

$$F = m\left(\frac{D}{X} - 1\right) \quad . \quad . \quad . \quad . \quad . \quad (6)$$

In preparing the final design this ratio must be determined in order to ascertain whether the steel stress or the concrete stress governs the design. A family of curves connecting F and X for various values of D is given in Fig. 3 for a modular ratio of 15.

(3.6) Application of the Charts to a Typical Design

The method of application of the curves described in Section 3.5 is demonstrated by the following example, which shows the method adopted in preparing the design of the 36-ft Class "D" pole.

The pole is required to carry an ultimate load of 2 500 lb applied 2 ft from the top of the pole, the upper kicking-block being 31 ft 6 in from the top.

Ultimate transverse resisting moment required	= 73 750 lb-ft
Depth of section (standard mould), d	= 11·41 in
Breadth of section (standard mould), b	= 5·34 in
Ultimate yield stress in steel, f_t	= 56 000 lb/in^2
Ultimate yield stress in concrete, f_c	= 3 600 lb/in^2 (assumed)
Modular ratio, m	= 15 (say)
Embedment depth, a	= 1·375 in

The total area of steel required, based on the "steel beam" theory, i.e. equation (1) of Section 3.5, to give a resisting moment R of 73 750 lb-ft is

$$\frac{24R}{f_t(d - 2a)} \text{ in}^2 = 3{\cdot}65 \text{ in}^2$$

Allowing 4—1$\frac{1}{8}$ in rods, $A = 3{\cdot}98$ in^2

The stress in the concrete of 3 300 lb/in^2 is less than the ultimate stress assumed for design. The design is therefore fixed by the steel stress and no further correction to the resisting moment is required.

Calculations show that the pole will fail under an applied bending moment of 79 727 lb-ft, equivalent to a load of 2 700 lb acting at 2 ft from the pole-top. The pole under test failed at a load of 2 800 lb, and an analysis of the stresses in the concrete and steel at this load is given in Section 3.8.

The first calculation for longitudinal strength gives a stress in the concrete in excess of the assumed maximum permissible, and corrections are applied accordingly (see Table 4).

The resisting moment of 20 800 lb-ft given by the above calculation corresponds to an ultimate load of 705 lb at 2 ft from the pole-top, which is in excess of the required load of one-quarter of the transverse load.

(3.7) Tests of New Designs

A pair of 36-ft poles of each class to the new designs referred to in Section 2.2 were fabricated and tested in a similar manner to the basic design except as regards the way in which the

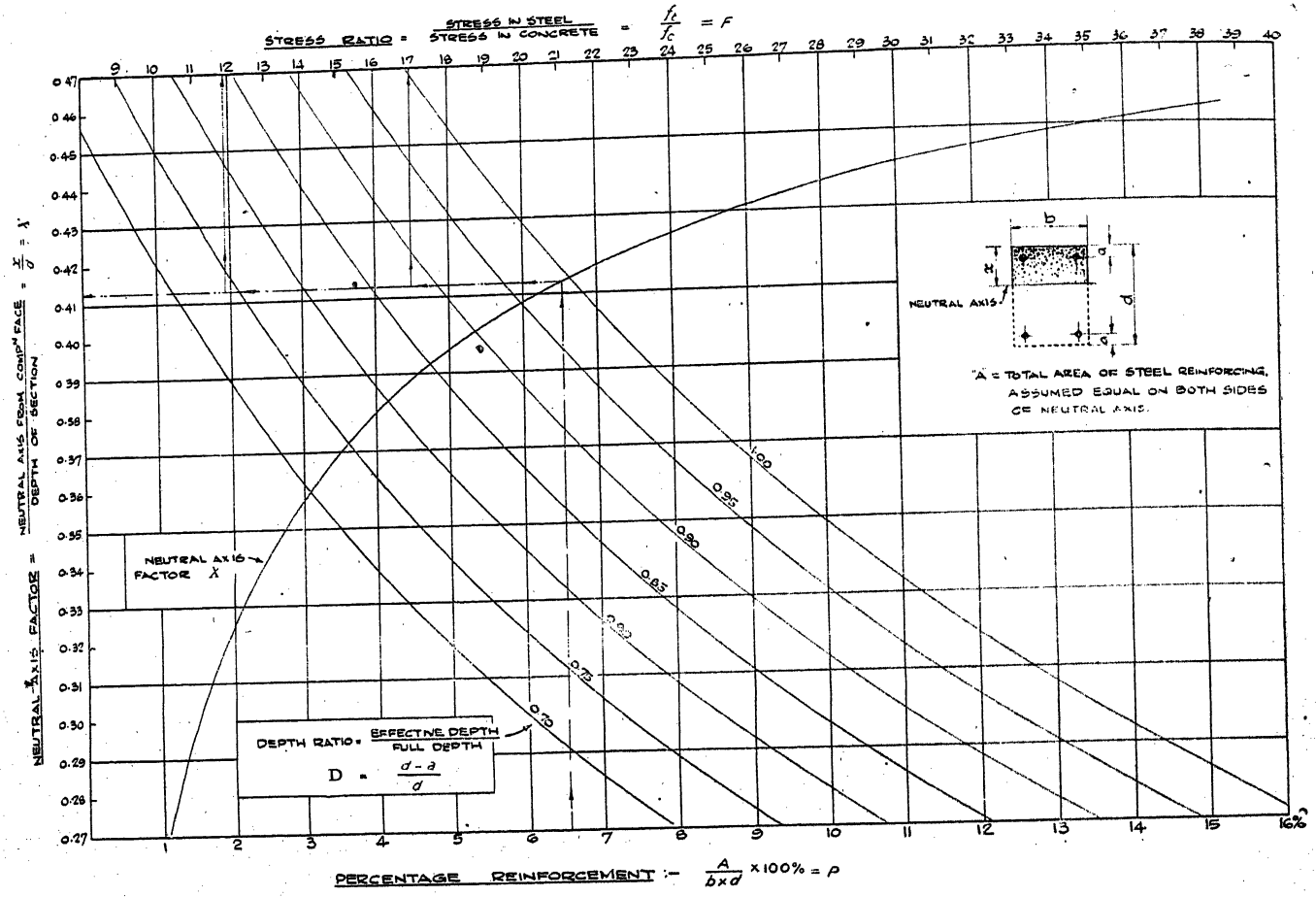


Fig. 3.—Reinforced-concrete pole design. Curves of neutral-axis factors and stress ratios, based on modular ratio $m = 15$.

Table 3

TRANSVERSE STRENGTH CALCULATION

Resisting moment by "steel beam" theory $= f_t \frac{A}{24}(d - 2a)$	80 400 lb-ft
Percentage reinforcement $= \frac{100A}{bd} = P$	6·53%
Value of X	0·4128*
Distance of NA from compression face $= Xd = x$	4·71 in
Depth ratio $= \left(\frac{d-a}{d}\right) = D$..	0·878
Ratio of stress in steel to stress in concrete $= f_t/f_c = F$	16·95*
Stress in concrete $= f_t/F = f_c$	3 300 lb/in²
Correction moment (negative) $= -\frac{f_c bx}{24}\left(\frac{x}{3} - a\right)$	673 lb-ft
Corrected resisting moment for $f_c = 3\,300$ lb/in²	79 727 lb-ft

* Factors marked with an asterisk are obtained from the curves (Fig. 3) described in Section 3.5.

Table 4

LONGITUDINAL STRENGTH CALCULATION

Resisting moment by "steel beam" theory $= f_t \frac{A}{24}(b - 2a)$	24 100 lb-ft
Percentage reinforcement $= \frac{100A}{bd} = P$	6·53%
Value of X	0·4128*
Distance of NA from compression face $= Xb = x$	2·21 in
Depth ratio $= \left(\frac{b-a}{b}\right) = D$..	0·742
Ratio of stress in steel to stress in concrete $= f_t/f_c = F$	11·88*
Stress in concrete $= f_t/F = f_c$	4 720 lb/in²
Correction moment (positive) $= -\frac{f_c dx}{24}\left(\frac{x}{3} - a\right)$	3 170 lb-ft
Corrected resisting moment for $f_c = 4\,720$ lb/in² ..	27 270 lb-ft
Corrected resisting moment for $f_c = 3\,600$ lb/in² ..	20 800 lb-ft

* Factors marked with an asterisk are obtained from the curves (Fig. 3) described in Section 3.5.

Table 5

Pole type	"B"		"D"	
Pole serial number	616	618	623	624
Date of manufacture	11.3.42	16.3.42	18.3.42	20.3.42
Date of test	9.4.42			
Main reinforcing bars (high-tensile steel to B.S. 548—1934)	4—$\frac{7}{8}$ in dia.		4—$1\frac{1}{8}$ in dia.	
Method of connecting bracing to main rods	Welded			
Cement used	"Ferrocrete"			
Fine aggregate	Sharp washed river sand			
Coarse aggregate	$\frac{3}{8}$ in crushed whinstone			
Concrete mix	1 : $1\frac{3}{4}$: $2\frac{3}{4}$ (by volume)			
Method of placing	Vibrated			
Load 2 ft from pole top at failure, lb	—	1 596	—	2 800
Deflection at pole top at failure, in	(24)	27	(22)	23

butts of the poles were bolted together. The tests on the basic designs had shown that fitting thick felt between the poles over the lower 6 ft did not correspond to normal working conditions, especially if kicking-blocks were used. The new designs were therefore tested by clamping the poles together only at the level corresponding to the top kicking-block. A timber packing-piece was fitted between the butts of the poles to correspond to the bottom kicking-block. With this layout the butts of the poles were subjected to heavier shear loads and were designed accordingly.

The results of these tests are given in Table 5.

Poles 618 and 624 failed at the top fixing clamp owing to the yield of the main reinforcing bars.

Compression tests were carried out on 6-in cubes manufactured from the same concrete mix as the above poles, with the results shown in Table 6.

Table 6

Date of test	11.4.42			
Pole serial number	616	618	623	624
Temperature during casting, °F	40	40	52	52
Breaking load, lb/in²	3 860	4 915	4 170	3 755

(3.8) Analysis of Tests on New Designs

(3.8.1) Stresses at Failure.

The results of the tests on the new designs were analysed in order to obtain the stresses in the steel and concrete when failure occurred. These stresses are given in Table 7, the methods referred to being those given in Section 3.4.

(3.8.2) Deflection.

The calculation of the deflection of a reinforced-concrete pole, owing to its composite nature, and also owing to the section not being uniform throughout its length, is not amenable to the usual methods. The method given in the Appendix was evolved to compare the calculated with the measured deflection.

The only unknown factor in equation (9) of the Appendix is the value of m, the modular ratio of the steel and concrete. Four values of this ratio were therefore assumed, and the deflection for a Class "D" pole calculated under an applied load of 2 800 lb; the results are given in Table 8.

The deflection given in Table 8 includes a correction for the reading being taken at 19 in above the applied load.

The actual measured deflection of the pole under test was 23 in.

It is of interest to note from the above deflection analysis that the value of m does not appear greatly to influence the deflection of the pole under test, and since the modular ratio varies inversely as the strength of the concrete the deflection reading of a pole under test does not give a true indication of the quality of the concrete used in its manufacture. Even if it is assumed that the concrete has zero modulus of elasticity and thus is incapable of taking any compression due to strain, the deflection is only increased to 29·9 in. In this extreme case all the compression is assumed to be taken by the steel reinforcement on the compression side of the neutral axis, the concrete acting only as a means of restraining the steel under compression. These conditions are brought about by the pole being equally reinforced on both sides of the neutral axis.

Table 7

Pole type	Pole serial number	Load at failure	Method "a"	Method "b"		
			Stress in steel	Value of m	Stress in steel	Stress in concrete
		lb	tons/in²	15	tons/in² 28·0	lb/in² 3 490
"B"	618	1 596	27·9	13	28·0	3 850
				11	27·9	4 270
				15	25·9	3 420
"D"	624	2 800	25·8	13	25·85	3 780
				11	25·8	4 240

Table 8

Value of m	9	11	13	15
Calculated deflection, in	22·8	23·5	24·1	24·7

A further point of interest regarding the deflection of reinforced-concrete poles is that for a given load the same deflection is obtained using equal areas of either mild or high-tensile steel, providing the stress in the mild steel does not exceed its yield point. This is because both qualities of steel have the same coefficient of elasticity.

It would appear that within the stress limits specified the deflection of a pole, fabricated with mild-steel rods and using low-grade concrete, would not vary greatly from that of a similar pole using high-tensile steel and high-grade concrete, and that deflection under proof-test loads cannot be taken as a criterion of performance and uniformity of manufacture.

(3.9) Stayed Poles

At angle and terminal positions the present practice is to use suitably stayed standard intermediate poles either singly or as H-poles. This is an outcome of wood-pole practice, but theoretically it would appear more satisfactory to use specially designed poles. The straight-line pole is designed as a cantilever, and the ratio of transverse to longitudinal strength at ground level may be as great as 4 : 1. When such a pole is used at a stayed position its resistance to crippling in its weaker direction is low, due to its relatively small depth.

A more satisfactory pole would be of square section, as it would be equally strong in both directions. The pole would be tapered from its mid-point towards both top and bottom, in order to reduce weight.

Experimental work by Thomas[4] has established that the ultimate strength of a short column is given by

$$W_c = 0{\cdot}65u(bd - A) + f_y A \quad . \quad . \quad . \quad . \quad (7)$$

Additional strength may be claimed if allowance for spiral reinforcement be made, but failure in long struts will occur by buckling and not by bursting, and it is doubtful, therefore, whether the addition should be allowed.

The design problem resolves itself into dividing the above ultimate strength by Rankine's correction,

$$\left[1 + \frac{e\left(\frac{L}{k}\right)^2}{C}\right]$$

where $e = u/(\pi^2 E_c)$ and k is the radius of gyration of the equivalent concrete section about an axis normal to the direction of buckling.

The calculated strength thus obtained gives results which prove satisfactory in service, but more experimental work will be necessary before exact results can be predicted by calculation.

(4) FABRICATION

(4.1) Works Arrangement

The cost of handling materials in the works has been reduced to a minimum. Steel frames are assembled in a shed close to the casting floor, the stock bars being on either side of the assembly shed. Small miscellaneous bending operations are carried out in a shed at the end of the yard. Sand and ballast are delivered to bins by means of tipping lorries, and concrete is mixed immediately in front of the bins. The poles are cast on a floor having a slight incline that aids man-handling by means of bogies to the curing bay under a gantry, by means of which they are stacked and later loaded on to the road transport vehicles for delivery either to station or to site.

(4.2) Fabrication of the Steel Frame

The steel frames used in the poles are of two types, one requiring diagonal bracing and the other having no bracing whatsoever except stiffening pieces to retain the frame in shape while the pole is cast. The frame is fabricated under cover in the assembly shed on benches fitted with jigs, electrical welding being used throughout. The assembly shed has been arranged to have an open front over its full length of 60 ft, the frames, if heavy, being allowed to slide on skid boards on to the casting floor. The efficiency of the welds is not of importance in the finished production, except for the jointing of main reinforcing bars. These must be jointed in certain cases since the maximum economical length of rod available is 36–40 ft. In the heavier designs of poles the use of bars of large section over the full length of 36 ft was found to be uneconomical, and short additional bars have been welded into place over the section carrying a maximum bending moment. A typical arrangement is shown in Fig. 3.

(4.3) Fabrication of the Complete Pole

Owing to the shortage of steel, timber moulds have been used throughout; each has been designed to be suitable for a range of pole lengths. The timber used is the ordinary grade of imported soft wood available, but hardwood inserts have been used for the semicircular shaping pieces. The frame is located in the mould by means of small pre-cast concrete buttons.

It has proved to be necessary to mix the concrete by hand. Tests have been made with concrete mixers of various designs, but in all cases, in order to obtain high-quality concrete, the low water/cement ratio required has caused the concrete to "ball" in the mixer, making it impossible to discharge it. Hand-mixed concrete is placed in the mould while the latter is vibrated. A standard 6-in test cube is taken for each pole cast and a technical record sheet is entered giving details of temperature and other conditions occurring during fabrication. The pole remains in the mould for 24 hours or more, after which time the top and sides are stripped and curing proceeds in the normal way, the concrete being kept moist.

The output with 7 men is 4 poles per day, and this has proved more than adequate for the demands made on the works. In off-times accessories of various types are made, stock maxima having been fixed in accordance with experience gained.

(5) ERECTION METHODS

(5.1) Delivery

Delivery for short distances is usually made by road transport by means of a special trailer drawn by a normal 2-ton lorry. Shorter poles are transported by lorry without the trailer, in a similar fashion to ordinary wood poles. In England, with its narrow entrances to fields, some difficulty is met in taking the poles direct to site by means of the trailer, and usually a transshipment has to be made on the roadside.

For longer distances poles have been despatched by rail, and so far no breakages due to handling by the railway company have been recorded.

(5.2) Erection in the Field

The reinforced-concrete pole weighs nearly double the wood pole it replaces. For the lighter and shorter poles the normal methods used for wood poles suffice, but for longer poles, more especially the heavier classes, special erection methods are required. The upper limit of erection by means of ladders or pikes is approximately 20 cwt, including top hamper, although determined foremen with reliable erection gangs frequently lift heavier poles than this. The alternative methods for heavy poles is the use of the standing and falling derrick. There seems to be a general preference for the standing derrick as the pole is handled with greater certainty, and difficulty is not encountered in sliding the butt down the skid-board.

(5) CONCLUSION

(6.1) Past and Present Practice in this Country

Wood poles for transmission lines are generally available in the three classes laid down in the British Standard Specification. Poles of other heights and diameters tend to prove uneconomical, since higher prices are charged by the manufacturers for altering standard stock sizes. Transmission-line estimates have therefore tended to be based upon the ranges of poles available, and this, in turn, has tended to fix span lengths. It would seem that undertakings considering using reinforced-concrete poles have, in the past, regarded them as suitable substitutes for wood poles, without taking into consideration the desirability of modifying the normal span of the line to take advantage of the relative cheapness of the heavier types of concrete poles. In pre-war days reinforced poles could not compete on these terms, except very occasionally in the case of steel-cored aluminium lines employing long spans. Spun-type reinforced-concrete poles have scarcely been used in this country. In pre-war days only one company appears to have offered hand-moulded poles, and the first 5 columns of Table 9 (referred to below) deal with poles manufactured and supplied by this company. B.S. 607—1935 has followed the practice of creating classes comparable with the corresponding wood pole, a Class "B" pole being the equivalent of a medium wood pole, and Class "D" of a stout wood pole. The various other classes legislated for give a wider range of choice in concrete than in wood, and Table 1 of the Specification probably meets all normal requirements. Table 9 of this paper gives replies to a questionnaire which was circulated to those undertakings known to have used hand-moulded reinforced-concrete poles. The total route length erected, as already observed, is remarkably small in relation to the large amount of work that has been done on this subject.

Three different modes of earthing the steelwork are shown as being in use, and no trouble appears to have been experienced with any of the systems. The use of kicking-blocks and foot blocks at foundations is largely a matter of foundation design and does not call for any special comment, except that, as the reinforced-concrete pole has a relatively small base area, it would be expected that a foot block would be used in all cases at angle and terminal positions, except in rock and rocky soil.

The economic length of the reinforced-concrete pole would appear to be limited at present to 60 ft, but there is no reason why longer poles should not be fabricated, provided there is a demand. A remarkably small number of failures have been reported and this, in view of the 4:1 transverse/longitudinal strength ratio, must be regarded as satisfactory. There is general agreement that the greater weight of the concrete pole is regarded as an important factor in the cost of a transmission line. In a recent investigation of a 3-phase transmission line, having $0 \cdot 10\,in^2$ copper conductors, without continuous earth-wire, 8 miles in length over normal rolling country in Yorkshire, it was estimated that the additional cost of supply of concrete poles would be £71 per mile, and the estimated increase in erection cost would be £13 per mile. These figures may be taken as fairly representative for any part of the country when heavy rail charges do not have to be met. No final estimate of the life of a concrete pole appears to have been reached, and it is interesting to see that there is no report in the replies received of spalling of the concrete from the reinforcing rods.

In a number of cases complaints are made that insufficient corings are allowed. Fig. 4 shows the corings standardized in one area of the country, and in order to achieve this standardization a complete re-design was necessary of most of the standard ironwork used by the undertaking. The authors suggest that the standardization of corings should be attempted for the country as a whole, following the lines of the recent paper by Willott Taylor and May.[5]

(6.2) Relative Advantages and Disadvantages of Concrete Poles

As with all products used commercially, the final justification for the concrete pole is a question of economics. In the past its advantage over the wood pole has never been very apparent, and this has been accentuated by the tendency to regard the pole as being suitable for direct substitution for the corresponding wood pole.

(6.2.1) Advantages.

It is claimed that maintenance is lower since little deterioration is to be expected. This claim holds good only if the concrete is of a dense character, such that moisture will not penetrate to the reinforcing rods. A cursory inspection of reinforced-concrete posts used extensively by the railway companies to fence their property will show that spalling does occur, largely owing to corrosion of steel, with a consequent bursting of the concrete around reinforcing rods. The solution to this, apart from the careful control of fabrication, may be to use one of the many proprietory brands of concrete sealing products which are now available.

It is claimed that, as reinforced-concrete poles are fabricated, a better control can be maintained of the quality. Against this must be borne in mind that the factor of safety of transmission-line poles has been reduced from 3·5 to 2·5 and that, therefore this claim must be discounted to at least a limited extent.

Long wood poles are difficult to obtain and are very dear. As already mentioned, this has tended to affect transmission-line design. Reinforced-concrete poles are relatively cheaper in the long lengths and, indeed, under present conditions are definitely cheaper. Under extreme conditions wood poles are likely to fail by breaking in the region of the ground-level section. The reinforced-concrete pole does not fracture completely and, even after the pole has failed so far as normal service is concerned, an emergency supply can be maintained on poles which have failed and require later replacement. Amenity advantages from a way-leave point of view can be claimed for the reinforced-concrete pole, and these advantages may well be enhanced if coloured concrete be used. There appears to be no danger of insect or bird action.

(6.2.2) Disadvantages.

The poles are much heavier than wood poles and, consequently, more expensive both to transport and to erect. They are not adaptable when line modifications are required, and tend, in effect, to be suitable only for important trunk lines.

They are difficult to use at special positions, owing to the need for ordering poles with additional corings which have to be fabricated to suit. The poles are more liable to damage in the event of conductor failure, owing to the 4:1 transverse/longitudinal strength ratio, and they are not well adapted to withstanding torsion loading. They have a negligible second-hand value.

(6.3) Possibilities of Future Use

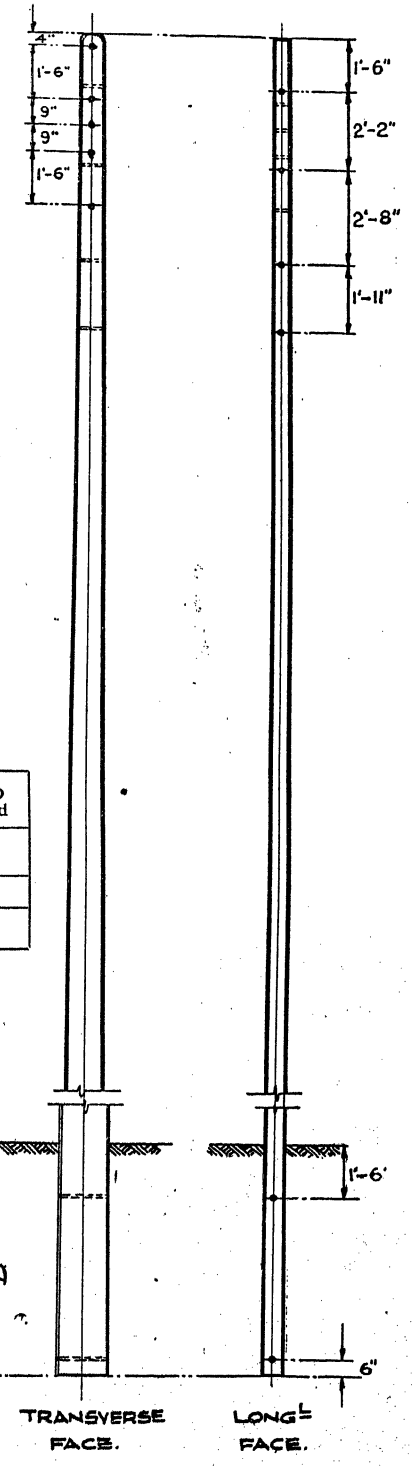
It would appear that the reinforced-concrete pole will prove suitable only for use on heavy types of construction. Special foundations will, however, be required, involving a fairly high field cost in the placing of concrete by hand after the pole has been erected.

It is interesting to note that certain accessories are now being fabricated at a lower cost than the corresponding wood article. This remark applies particularly to stay-blocks.

Present conditions are, however, largely artificial, and it is difficult to forecast what will occur when more normal conditions returned. Wood poles have the advantage that large stocks

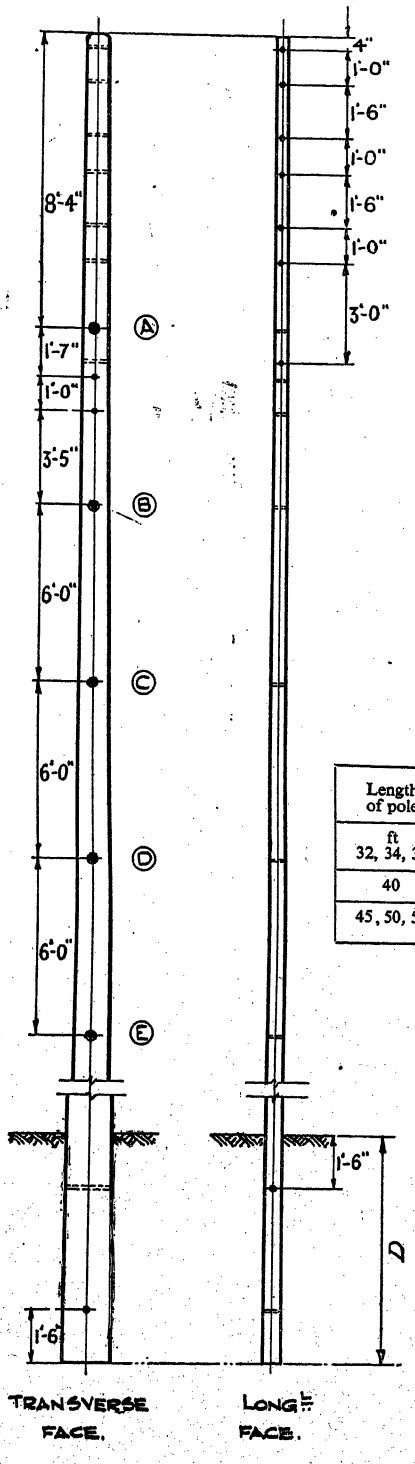
Table 9—Replies to Questionnaire Regarding the Performance of Reinforced-Concrete Poles Under Working Conditions

Undertaking	Electricity Board for Northern Ireland	Exe Valley Group	Chester Corporation Electricity Department		West Devon Electric Supply Company	Bournemouth and Poole Electricity Supply Co., Ltd.	North-Eastern Electric Supply Co., Ltd.
Route lengths of lines in service, miles	14	95	36	22	42	3	37
Voltage	33 kV	33 and 11 kV	6·6 kV	L.V.	11 kV	L.V. distribution	3, 6, 11 and 20 kV
Mode of earthing steelwork	Earth lead cast in pole	Earth lead cast in pole	Earth lead cast in pole		Earth lead cast in pole	No earth lead	Heavy poles — Earth lead clipped to pole. Light poles — Reinforcing rods used as earth lead
Foundations:— (*a*) Kicking-blocks (*b*) Foot blocks	In soft ground Fitted	In soft ground At angle and section poles	None As necessary		At marsh positions None	None None	Fitted Fitted
Range of pole heights, ft	56–32	50–32	44–29		42–34	32–26	55–28
Pole failures in service due to:— (*a*) Abnormal conditions	None	None	Falling trees caused failure of two poles		None	None	None
(*b*) Snow, wind and ice loading	None	None	None		None	None	None
Is weight of reinforced-concrete pole important factor in cost of line?	Yes Weight also increases risk of damage when access to site is difficult	Yes	Yes—due to extra transport and labour costs		Yes — due to extra transport and labour costs	Not a very large factor	Yes
Erection method	—	Standing derrick	Light poles — falling derrick Heavy poles—standing derrick		Standing derrick with fitted winch	Standing derrick in most cases	Falling derrick
Estimate of probable life of poles	Line erected in 1933 shows no deterioration except some fine "hair" cracks	Indefinitely long	Appears to be indefinite		Appear to be in perfect condition after 9–10 years' service	Not sufficient data to give an estimate	Not sufficient data to give an estimate
Is difficulty experienced due to lack of corings when additional apparatus has to be attached?	Yes, this is rather awkward at times	No	Yes		Yes. A wood pole is occasionally substituted. Alternatively clamps are used	No special difficulty	Corings have been designed to fit standard apparatus, otherwise difficulty would be experienced
Suggested improvement in existing design	Cored holes should be cast when pole is manufactured, to take additional fittings which may be needed later	None	Both h.v. and l.v. poles should have earth wire cast into pole. The largest possible number of bolt corings should be allowed		—	None	None
Is the extra cost of concrete over wood poles justified?	I do not think so, provided the wood poles are of the best possible quality, properly treated before use	Yes	Yes		Only for trunk lines	No	Provided imported red fir poles are available, the extra cost of reinforced-concrete poles is not justified



Length of pole	Depth *D* in ground
ft 32, 34, 36	ft 6
40	7
45, 50, 55	8

SINGLE-MEMBER POLES.



Length of pole	Depth *D* in ground
ft 32, 34, 36	ft 6·5
40	7
45, 50, 55	8

"H" POLES.

Notes.

1. All holes suitable for ¾ in dia. bolts.
2. Holes shown thus ⊕ are common to all pole lengths.
3. Holes shown thus ⊙ are to take trussing tackle, their number and position for various pole lengths being in accordance with the Table on right.

Length of pole	No. of sets of tackle	Position of cored holes
ft 28, 32, 34	1	A, B
36 40	2	A, B, C
45, 50	3	A, B, C, D
55	4	A, B, C, D, E

Fig. 4.—Typical standard corings.

can be accumulated at the suppliers' works, and these can be drawn upon at very short notice. Reinforced-concrete poles can be handled in a comparable manner, only if standard bolt-hole corings are adopted.

At the present time the possibilities of improvement of design are limited by the special steels available. If a steel could be produced having a yield point of the order of double that of the present high-tensile commercial steel, the weight of the reinforced-concrete pole could be reduced to compare with the corresponding wood pole. Special steels will probably be available after the war, and it will then be possible to approach the whole problem afresh with the certain expectation of producing a really satisfactory design. Until then the full possibilities of using the available strength in the concrete will not have been realized.

(7) ACKNOWLEDGMENTS

The authors wish to express their thanks to the supply authorities named in Table 9 for replies giving details of their experience and practice. They are also indebted to members of the staffs of Messrs. Merz and McLellan, the North-Eastern Electric Supply Co., and Riley and Neate, Ltd., for numerous suggestions made and for their co-operation in the development of the designs.

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(9) APPENDIX

(9.1) Symbols

A = total area of four main reinforcing bars (assumed of equal area).
b = breadth of section.
d = depth of section.
P = percentage reinforcement = $100A/(bd)$.
a = embedment depth of main reinforcing.
D = depth ratio = $(d - a)/d$.
E_s = modulus of elasticity of steel.
E_c = modulus of elasticity of concrete.
m = modular ratio = E_s/E_c.
f_t = tensile stress in steel.
f_c = maximum compressive stress in concrete.
F = stress ratio = f_t/f_c.
x = distance of neutral axis from compression face.
X = neutral axis factor = x/d.
t = distance from neutral axis to tensile reinforcing.
c = distance from neutral axis to compressive reinforcing.
W = applied load.
M = bending moment due to applied load.
R = resisting moment of beam.
L = distance of applied load from ground level.
l = distance from ground level to section under consideration.
ρ = radius of curvature of pole at section under consideration.
W_c = ultimate axial compressive load.
u = cube strength of concrete.
f_y = yield point stress of steel.
C = constant determined by the fixity of the ends of column.

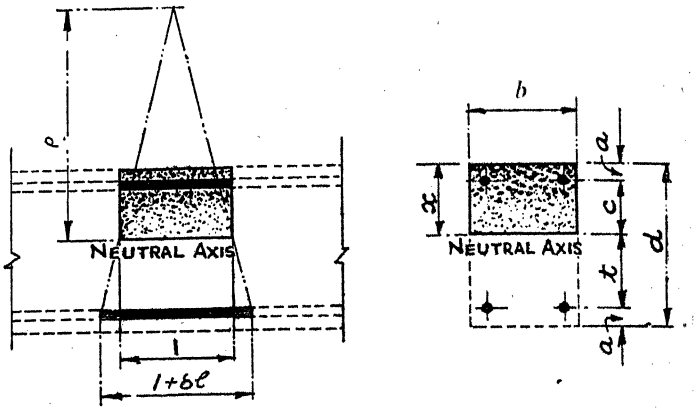


Fig. 5.—Method of calculating deflection of reinforced-concrete pole.

(9.2) Method of Calculating Deflection of Reinforced-Concrete Pole

In Fig. 5 let δl be the increase in length per unit length of the main tensile steel due to stress f_t at distance l above ground.

Then $$\delta l = \frac{f_t}{E_s}$$

and $$1\Big/\left(\frac{d^2y}{dl^2}\right) = \rho = \frac{t}{\delta l} = \frac{tE_s}{f_t} \quad \text{or} \quad \frac{d^2y}{dl^2} = \frac{1}{E_s}\left(\frac{f_t}{t}\right) \quad . \quad . \quad (8)$$

$$M = R = \frac{f_t b x^3}{3tm} + \frac{f_t A t}{2} + \frac{f_t c^2 A}{2t}$$

$$= \frac{f_t}{t}\left[\frac{bx^3}{3m} + \frac{A}{2}(t^2 + c^2)\right]$$

Substituting in (8) above for $\frac{f_t}{t}$ we obtain

$$\frac{d^2y}{dl^2} = \frac{1}{E_s}\left[\frac{M}{\frac{bx^3}{3m} + \frac{A}{2}(t^2 + c^2)}\right]$$

The deflection at the point of application of the load is

$$y = \frac{1}{E_s}\int_0^L \int_0^L \frac{M dl dl}{\left[\frac{bx^3}{3m} + \frac{A}{2}(t^2 + c^2)\right]} \quad . \quad . \quad . \quad (9)$$

An approximate value of the above integral can be obtained by the use of Simpson's rule.

Let $\dfrac{M}{\left[\frac{bx^3}{3m} + \frac{A}{2}(t^2 + c^2)\right]}$ have the value Z_1 at ground level and Z_2 at a point mid-way between ground level and the applied load.

Then equation (9) becomes:—

$$y = \frac{L^2}{6E_s}(Z_1 + 2Z_2) \quad . \quad . \quad . \quad . \quad (10)$$

DISCUSSION BEFORE THE TRANSMISSION SECTION, 8TH MARCH, 1944

Mr. C. O. Boyse: This excellent paper draws attention to some of the pitfalls which await the unwary maker of concrete poles. In particular, the authors have rightly emphasized the vital importance of knowing the ultimate strength of a pole, the calculation of which needs to be checked by type tests.

The authors suggest a definition of failure to replace that in B.S. 607, which is now under review, whereas I think the following is to be preferred: "Failure is defined as the condition when the pole ceases to function in the designed manner, due to permanent stretching of the reinforcing rods in any part of the pole or to failure of the concrete on the compression side of the pole. This condition is reached when permanent set begins to show marked disproportionate increase with load."

The control of quality in bulk manufacture is the most difficult problem of all owing to the nature of the product. The authors emphasize the need for strict supervision in the works, and they realize that faults in manufacture cannot easily be detected afterwards. In consequence, they rightly criticize the programme of routine tests in the present B.S. 607. As we now know, the deflections of concrete poles under proof tests are not related to the actual ultimate strengths of the poles. Consequently, although we must agree that routine tests on selected poles are desirable in the interests of both the maker and the user, it is not easy to see how the results of these tests should be interpreted.

It has been proposed that, amongst other changes in B.S. 607, the present routine tests should be abandoned in favour of proof tests up to 60% of the ultimate strength of the poles, carried out on 10% of each batch. Provided that any hair cracks that appear during these tests clearly close up when the loads are removed, the poles shall be deemed to have passed the test. It is also suggested that deflection readings should be taken during the tests for the purpose of record, on the assumption that these readings will eventually add to our knowledge of concrete-pole performance under load. It is realized that this proof-test routine is open to criticism, and it is possible that the authors may be able to suggest a more satisfactory procedure.

On the question of weights it is interesting to consider the amount of steel required in concrete poles. Taking as an example the 40-ft Class "EX" pole referred to in Fig. 1, this weighs $26\frac{3}{4}$ cwt and includes $6\frac{1}{4}$ cwt of steel. A light lattice steel pole of the same strength and length would weigh just over $7\frac{1}{2}$ cwt. Similarly, a 45-ft Class "D" pole as shown in Fig. 2 weighs $25\frac{1}{2}$ cwt and contains $5\frac{1}{2}$ cwt of steel. The corresponding lattice steel pole of the same strength weighs $7\frac{1}{2}$ cwt. It is therefore clear that the amount of steel saved by using reinforced concrete, while of some importance in war-time, is not nearly as great as might first be thought.

The authors refer to stayed poles and to the compressive stresses in them. They should have pointed out that other stresses must also be considered in stayed poles, for even when stays are placed at the centre of the load secondary bending stresses are created and these are usually of considerable importance. It is not sufficient to consider merely the compressive strength of a stayed pole.

Much work has been done recently on the pre-stressing of reinforcement in reinforced-concrete structures. I would like to know whether the authors have considered adopting this procedure for their poles, although it is possible that the advantages of pre-stressing would not be fully realized in this case.

The general experience of users of reinforced-concrete poles in this country has been very satisfactory. Nevertheless, these poles do suffer serious damage in the event of broken wires. They are not, of course, designed to resist broken wires any more than is the ordinary wood pole, but a concrete pole by reason of its lack of flexibility cannot yield to a twisting moment, and on several occasions when conductors carried on concrete poles have broken for one reason or another the pole tops have been twisted off. Under similar conditions a wood pole would rotate in the ground or the cross-arm would fail, but in neither case would the pole be permanently damaged. For maximum reliability, supports which are not strong enough to resist broken wires should be sufficiently flexible to deform without suffering damage.

Mr. P. J. Ryle: On all poles of the types described, which I have seen tested, hair cracks have appeared on the tension side at well below the ultimate load, but on removal of loads below the ultimate these cracks have closed up completely as far as could be seen with the naked eye. The non-closing of the cracks for higher loads has always been surprisingly clearly defined and corresponds closely with the B.S. 607 criterion of failure, i.e. "the load at which permanent set begins to show marked disproportionate increase with load." Observation of non-closing of cracks is thus a useful confirmatory guide to the "failure" load.

I agree with Mr. Boyse on the need for detailed consideration of the concrete pole when used as a strut. Sometimes there may be considerable bending as, for instance, on a stayed terminal pole carrying a heavy off-set transformer, when the pole is called upon to act as a heavily loaded strut with appreciable eccentric loading.

There is very little reference to cross-arms in the paper. The poles which the authors describe have all been used with steel cross-arms; in my opinion the steel cross-arm is much the most attractive type for reasons of both appearance and general adaptability. It is easily adaptable for special positions, and replaceable if outlasted, as it should be, by the pole itself. Different types of cross-arm may be needed for different types of road and railway crossings, etc., and as long as enough cored holes have been supplied in the pole itself, this should not lead to any difficulty. Fig. 4 shows the standard arrangement of holes provided in these poles; there are not very many, but it is surprising how many different jobs can be catered for with these cored holes. Have the authors given any consideration to the advantages and disadvantages of concrete cross-arms?

Regarding the vibrators which the authors use in setting the concrete, what sort of frequency and what sort of vibrating masses are used, and how is the vibration actually applied to the mould?

The authors do not say much about earthing. Early doubts as to the desirability of earthing on concrete poles via the reinforcement were, I think, justified, because the joints in the main members were simply lapped joints, mechanically sound but most unsatisfactory from the electrical standpoint. Present-day joints are all-welded, and there is no reason why the reinforcement should not then be considered as a perfect earth lead as long as good connections can be ensured at the top and bottom of the pole.

It is a pity, if the authors are right, that 60 ft is about the economic limit of height for these poles. In France and Italy poles of up to 80 and 90 ft are sometimes used. I do not know whether they are economical or not, but they have certainly often been handled and erected in the most awkward places. If poles of the general type described in the paper could be economically supplied and erected up to about 70 ft long, there might be a field for them for, say, 33-kV or 66-kV double-circuit lines with suspension insulators.

The weights of the poles described in the paper, if plotted against $H\sqrt{M}$, where H is the overall height in feet and M is the maximum working bending moment in lb-ft, fall very nearly on a straight line $W = 0{\cdot}35\,H\sqrt{M}$, where W is the pole weight in

lb. I have always found that the weights of lattice steel towers can be closely approximated by $W = 0{\cdot}12\,H\sqrt{M}$, so that the complete concrete pole weighs approximately three times as much as a steel tower for the same job. Now the steel reinforcement in a concrete pole represents about 24% of its total weight, so that the weight of steel in the pole is never much less than about 70% of the weight of steel in the corresponding steel tower. It is therefore clear that concrete-pole construction does not save much in steel, and can very rarely show a saving in initial cost. Its chief advantage, in normal times, must therefore lie in durability and absence of maintenance costs. Long-term experiences of users should therefore be welcomed.

Mr. P. B. Frost: The Post Office do not use concrete poles, although in peace-time we use a total of about 250 000 poles a year. The possibility has been carefully studied at intervals during the last 20 years; the last time was in 1942, owing to the very high cost of timber, but the decision has always been emphatically against using them. Our reasons for this are, first, transport. We have 9 000 engineering vehicles in use; many are called upon to carry 1, 2 or 3 poles, and some full loads. If we adopted a pole much heavier than wood, many of our vehicles would have to be replaced by heavier ones. Better and more lifting appliances, and even mobile cranes, would be needed, apart altogether from more men. In the usual installation gang every man has his job, and a larger gang could not be employed economically.

Again, new designs of pole fittings would be needed and more stocks would have to be carried, or, alternatively, we should want poles with very many cored holes; this, as the paper points out, would present considerable difficulty. The risk of damage in handling, both in transport and in erection, in shifting from the stack to the lorry and in unloading the pole at the roadside, is very much greater with concrete than with timber poles. Freight charges, too, are much higher. A point which affects us particularly is the single linesman who goes about on a motor-cycle, or at most on a motor-cycle and sidecar; he cannot take a ladder, and always uses climbers. I do not think that there is any suitable climber for use with concrete poles.

Comparisons of costs and weight depend upon the factors of safety taken. Assuming $3\frac{1}{2}$ for timber and $2\frac{1}{2}$ for concrete, on actual quotations obtained in 1942, the cost for concrete poles works out at over four times that for timber, while the weight is from three to six times greater. These figures alone rule concrete poles out for the relatively small sizes that the Post Office makes most use of.

With regard to the life of poles, I do not see why a concrete pole should fail, except perhaps by spalling. This does happen, but could be avoided by controlled mixing conditions, vibrated concrete, a small aggregate and a low water content; moreover it is only rough, cheaply-made posts which fail in this way. The life should be at least equal to the recognized life of imported timber, say 40 years. I do not claim that creosoted timber may be depended upon to give a longer life than this, although we have very many poles still standing after well over 50 years' service which are still in perfectly sound condition.

There are two points in the paper with which I do not agree. One is the reference to the unfortunate results in the use of larch. We have many larch poles standing which were erected in the last war and which are still quite sound; but a considerable number have failed. Their life is in fact somewhat erratic. The other point is the statement that timber usually breaks at or about the ground line. That is not true for the heavier and taller timber, which frequently breaks well above the ground line. Theoretically, for poles carrying a single concentrated load the weakest point is where the diameter is $1\frac{1}{2}$ times that at the load point. Poles 50 ft long should break at about 10 ft above the ground level, while 70 ft poles should break at 30 ft above ground.

I think the paper deserves high praise for the fair comparisons made, and that the claims made for concrete can be accepted as justified.

Mr. E. S. Broadhead: Any engineer who is called upon to design a structure to a specified factor of safety will find that the standard textbooks give him almost no guidance as to the behaviour of a structure as it approaches failure. Many engineers believe that if they design for a stress one-quarter of the stress of failure they will get a factor of safety of 4. For steel transmission towers we should have a factor of safety of about $2\frac{1}{2}$, which may be further reduced by deflection and secondary stresses. With a concrete pole the complications are even greater, because the percentage of steel used is about 10 times more than in ordinary construction, whilst the breadth of a pole may be only one-hundredth of its height.

I have designed several concrete poles, and realize the difficulties of designing without proper knowledge. None of these poles was ever manufactured, so that I have no idea how they would have behaved under test. P. D. Morgan exhaustively summarized existing knowledge in his paper [Section 8(2)], but gave no advice on stresses at failure or factors of safety. The present paper does give this vital information. The tests made show that the steel-beam theory works satisfactorily, and that the compression flanges will not fail otherwise than as a column when the ratio of length to breadth is about 100. Designing without this knowledge is not much more than intelligent guesswork at the best.

I do not agree with the authors on the proportion of the pole which should be underground. They advise designing a pole as if kicking-blocks are to be used, but this is perhaps the best condition, except, perhaps, where the pole is cast in a concrete block. Any other condition will reduce the lever arm of the resisting moment, so that the shear stresses must be increased beyond those where the kicking-block is used. As it is impossible to guess the future condition of the ground, and as the shear can be carried so easily, a higher factor of safety for this portion of the pole appears rational. I am not advocating a safer foundation; I favour the foundation being the weakest part of the line. It is much easier to plumb a pole than to replace it with a new one.

The authors say that there seems to be no measurable difference in the behaviour under test of two poles of different quality, until failure occurs. Deflection gives no guide to quality either of steel or of concrete. From this it follows that the only way in which the user can safeguard himself is to have a few poles tested to destruction and be certain that all the other poles are made of the same material and with equal care.

After the war, the country may not be able to afford the luxury of imported wooden poles when a reinforced concrete substitute, made of home-produced materials, can be provided, so that there may be a bright future for the reinforced-concrete pole.

Dr. J. McCombe: For some years I was with the Electricity Board for Northern Ireland, where we had upwards of 300 concrete poles, which behaved well. The concrete pole has increased in use during the war, owing to the scarcity of Baltic timber. The only timber now available is home-grown, and while Scotch fir, larch and spruce are as strong as the Baltic variety, their life is doubtful.

Investment is made in a concrete pole as a long-term policy, but most designers fit it with a steel cross-arm. Recently I analysed the life of steel cross-arms in industrial areas, over a period of about 16 years, and found that the average life of a galvanized cross-arm is about five years in such areas. At the end of that time it can be wire-brushed, given a coat of red lead

followed by a coat of sublimed lead and finished by a coat of chromium oxide; this treatment is expensive, takes time, and means that the lines are out of commission. Or the cross-arm can be left in a rusty state for a few more years and then scrapped. With a long-term policy of purchasing poles of the concrete type, surely the integral parts should have an equivalent life?

I disagree with the authors' statement that concrete poles may be used in future for the heavier trunk lines, as I cannot see anything replacing the steel tower for the 132-kV lines. With regard to the 66-, 33- and 11-kV lines, the tendency has been for the pendulum to swing towards all-insulated lines. If that pendulum swings further, as I believe it will, the principal component of such lines will be the wood pole, with its high impulse strength; there is thus no field for the concrete pole. On the other hand, with the large post-war building programme which will be closely watched by the usual town-planning committees and societies for the preservation of rural England, the question of amenities must be considered and will, I think, mean a place for the concrete pole on low-voltage distribution, but certainly not for main trunk lines.

Regarding the weight of reinforced-concrete poles, the authors refer to the future use of the higher-tensile steels and pre-stressed steels as a means of reducing weight. For any appreciable reduction in weight, I feel they must think in terms of lighter aggregates.

Mr. H. G. McDowell: This very informative paper is of particular interest to me, as I have recently been concerned in the design and manufacture of concrete poles for a transmission line. In studying the designs in the paper, I am struck by the narrow width of the longitudinal face, and it would be interesting to know whether the relative weakness in this direction complicates handling and erection. It would appear that great care must be exercised to prevent cracking of the concrete, and I presume that the poles must always be kept on edge. I gather that the same section is used for stayed poles.

The importance of the cover to the steel has been emphasized. I favour a generous cover, although this, unfortunately, increases the weight of the pole. The poles to which I have referred are of H-section with ribs at 2-ft centres. We decided on 1 in of cover, which gave a rather thick flange, and, as the bulk of the weight is in the flanges, the poles are rather heavy. The poles are square in section, so that the strength in the direction of the line is considerably more than one-quarter of the transverse strength; they were designed so that intermediate and stayed poles, from 36 to 48 ft in length, could be made in the same type of mould. The design is admittedly conservative, but in erecting the intermediate poles bending will occur about the Y–Y axis, so that the considerable strength in this direction is an advantage, particularly as the cross-arms are of concrete.

The replies to the questionnaire are encouraging, and make one hopeful of the future use of concrete poles.

Mr. G. R. Falkiner Nuttall: My own experience with concrete poles goes back to France just after the last war, when I was engaged in reconstruction work there. The poles described in the paper are in some ways similar to those then employed; a great deal of progress in the way of design does not seem possible. All the poles in France were designed in accordance with the 1906 regulations, and even in current calculations I still use the 1906 French code.

On the Continent, the practice is to use rather spidery steel arms, which whip round the pole if anything goes wrong. In this country, on account of corrosion, concrete cross-arms have been used, but they have the disadvantage that there is very little give in them. In 1940, I carried out some experimental work with M. Lambert, one of the engineers on the French Railways, which led us to conclude that we would not need any insulators on the arms; and that we could make a concrete cross-arm which would itself be an insulator. I brought the material to this country and had it tested by the National Physical Laboratory with striking results.

I agree with the authors that 60 ft should be the approximate limit of height of a pole. I do not agree that larger poles should be made in concrete; steel is the right material for them. On the Continent the ordinary distribution-line concrete pole, which is quite a light pole, is used in very large quantities, although timber is available.

Major T. Rich: The first concrete posts for power transmission were erected in the Dresden and Grenoble districts about 1909, mainly as an advertisement for concrete. Some of the first French poles were wooden posts with cement round them, but the wood swelled and cracked the cement. I think that the mistake still made in this country with spun posts and spun pipes, is that the concrete is used too liquid.

In this country posts have to be imported; high-grade timber is used, well creosoted, and their long life does not encourage the use of concrete for line posts. On the Continent, inferior wooden posts have been much used for railways and for telegraph lines generally; they have rotted at the base and have then been repaired by supporting by prickers without disconnecting the conductors and by cutting at the ground line and putting on a concrete base. The same post then lasts almost indefinitely. I think in this country a good concrete base with a wooden post above might serve for some light lines.

When the C.E.B. first made a specification for a concrete post, they decided that the cross-arm must be built to stand the torsional strain. German engineers, on the other hand, put up several high-voltage lines with lattice supports on the principle that if there is a variation in stress the cross-arm will react to it and adjust itself. Is the post to be turned into a testing-machine or should simple arrangements be provided for adjustment? That can also be overcome by not making the attachment too strong; if the line slips it does not do much harm, and the cross-arm is relieved. The other method is to allow the cross-arm to give.

There are several types of post not mentioned in this paper which have had a considerable vogue on the Continent. One type uses rapid-hardening cement, Ciment Fondu, in positions where aggregate is very cheap. Several power lines have been put up in mountainous districts in Spain with the posts cast on the spot and erected about three days after being cast, the line being put up a few days later.

Another reason why more concrete posts are seen on the Continent is that the lines are usually along the roads, so that transport difficulties are not as great as with cross-country lines. For making poles steel moulds are used and last a very long time; they give a good surface.

Have the authors had any experience with notched bars or specially-shaped bars? Pre-stressed bars have been tried on the Continent, but up to the present the results have not been worth the trouble.

Mr. W. K. Allen (*communicated*): The authors are to be congratulated on the design of a pole combining a low weight to strength ratio with good appearance. Concrete cross-arms are not mentioned, but on straight-line poles these have proved quite reliable and give a finished appearance to the line.

Whilst agreeing that the use of home-grown wood poles is not desirable on lines forming a permanent part of the transmission system, I think that careful consideration should be given to the respective merits of steel and reinforced concrete. It is not generally appreciated that a sectional tubular steel pole, with its manifold advantages from the erection point of view, will have an overall weight of no more than the weight of rein-

forcement alone in an equivalent concrete pole. With copper-bearing steel, careful galvanizing and proper precautions against internal condensation, this type of support will give every satisfaction. Angles and terminals can be dealt with either by modification of the tubular pole or lattice towers.

Erection of heavy reinforced-concrete supports involves scrapping most preconceived ideas and evolving a new technique. I have had some success with a 4-wheel drive, 4-wheel-steering tractor fitted with an anchor and a power-driven winch. The poles are transported six or eight at a time from the railway station to site by the tractor and a trailer capable of carrying up to 18 tons. A single derrick suitably guyed is used for erection, the pole being picked up from the trailer at a point one-third of its length from the top, employing a block operated by the tractor winch. It is lifted clear of the ground and can then be easily lowered into the hole. The authors' estimate of an increased erection cost, compared with a wood-pole line, of £13 per mile would appear to be conservative.

There is very considerable advantage in the use of a foundation giving adequate initial strength with the minimum of excavation. A power-driven auger can be used to drill a hole of exactly the required diameter to give foundation strength. The pole is placed upright in the hole and the space filled in with 1½ in washed ballast: the pole will now stand upright, and the foundation develops considerable strength. Liquid grout is poured on to the ballast, which then sets into a vertical kicking block of exactly the required dimensions. I have found this type of foundation to give excellent results; it can be adopted with success on a wood-pole line, when the grout can usually be omitted.

Have the authors considered the possibility of utilizing the reinforcement in place of an earth wire down the pole? Subject to careful welding, the area of reinforcement should be sufficient to carry considerable fault current without undue heating of the rods and consequent spalling of the concrete.

I should like to make a plea for the use of pigmentation, preferably brown, as a line of natural-coloured concrete poles contrasts harshly with the countryside.

Mr. A. Burke (*communicated*): I suggest that sectional plans be inserted in Fig. 1 to explain the varied references to I, H and U sections and to show how the bracings have sufficient cover when flutings are used.

Were the failures judged by the authors' proposed criterion or, if not, will they say at what percentage of the stated loads the load/deflection curve ceased to be linear? Were any of the poles tested to destruction and, if so, what was the maximum load withstood?

The tests indicate that failure occurs at about the yield stress of the steel. Have the authors considered loading the bars before assembly to nearly breaking stress? Steel treated in this way has no definite yield point on subsequent loading, and hence poles fabricated with it should show nearly 50% increase in strength. Before finally accepting this principle, it must be shown that the pre-stressed steel behaves in compression the same as in tension, and does not revert to its former condition under the influence of normal variations in stress and temperature. To take advantage of such high stresses in the steel, it may be necessary to have a higher-grade concrete than that for which particulars are given in the paper. This is a factor which does not appear to have been considered when dealing with special steels in Section 6.3. The question of tension cracks was also ignored.

Spun poles should not be lightly dismissed, although there may be some difficulty in providing for heavy shear loads, and their greater dimensions may be undesirable in footpaths. The concrete has a dense durable surface and, being about twice as strong as that mentioned in the paper, is better adapted to the use of any special steels which may come on the market. A calculation for a 36 ft Class B circular pole indicates that, while it is equally strong in all directions, the total weight and the quantity of steel are not much more than for the authors' rectangular pole. To compare their value for a conductor break, assume that both poles are first stressed transversely by a load P and then that a longitudinal load $0{\cdot}5P$ is added. The stress in the authors' pole is increased by 200%, but that in the circular pole by only 12%. It is worth paying extra for this big advantage, even though the Regulations permit a longitudinal strength of a quarter of the transverse strength. Again, the circular pole is better as a strut, which is important on main rural lines when many branches are subsequently added; it appears that the rectangular pole would have to be replaced by a square one when a stay is fitted.

Mr. C. Wade (*communicated*): I take it that a concrete pole under ordinary conditions, and if well constructed, may last indefinitely, but wooden poles have in many cases shown a life of 50 or even 70 years. Replacements of wooden poles have been very few in the last 40 or 45 years, according to my experience. No doubt there may be an opening for concrete poles, but I think that wood poles will continue to be used.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. E. C. Neate and **W. F. Bowling** (*in reply*): The interest with which the paper has been received is much appreciated, and we regret that limitations of space prevent our replying more fully to the points raised in the discussion.

The definition of failure by Mr. Boyse is that drafted for the proposed revision of B.S. 607. The principal difficulty in meeting its requirements is that the permanent set is very small relative to the total deflection of the pole under load. In answer to Mr. Burke's question, the poles were tested to our proposed definition and, owing partly to the conservative design and partly to the use of rods of stock diameters, failure occurred between 10 and 15% above the declared ultimate strength. We agree with Messrs. Boyse and Broadhead that in the present state of the technique a routine test gives no information as to the likely performance of a pole in service. We think that reliance must be placed on careful supervision during manufacture, the results of the concrete cube tests, and the steel manufacturer's test report.

The weights of lattice steel poles given by Mr. Boyse are on the high side; a 45-ft lattice steel pole to correspond with a Class "D" pole can be designed to a weight of less than 6½ cwt, but unfortunately this pole, while cheaper to fabricate and erect, suffers from high maintenance cost.

The strut formula given in Section 3.9 deals with the straightforward case of a pole in direct compression, and if compression combined with bending has to be catered for, the usual adjustment to the calculations must be made.

Several speakers have raised the question of the use of pre-stressed steel. Conditions in war time have been too difficult to enable us to take advantage of the increased yield stress obtained by this process. Light aggregates usually have the disadvantage of being porous, thus risking corrosion troubles.

Mr. Boyse has shown some interesting photographs of a failure due to broken line conductors. We think that the following details of field tests of an "EX" pole may be of interest. With all conductors and earth wire broken, the damage was limited to the poles on either side of the break. The flexibility of the pole in the longitudinal direction combined with the

failure of the steel cross-arms relieved the tension in the conductors. The pole was then tested in the transverse direction, and failure occurred at 75% of the design figure. We agree with Mr. Ryle that the use of steel cross-arms is preferable to the more rigid and much heavier concrete arm. Dr. McCombe's experiences of cross-arm corrosion appear to be exceptional.

The vibrators employed are a proprietary article, the vibration being caused by an out-of-balance rotating armature. Two, clamped across the moulds, are used for the average length of pole.

The main reinforcing has been used for earthing on lighter lines and has proved quite satisfactory, but on the heavier types of poles there has been a general preference to run a separate external earth-wire.

The 60-ft economic limit is based on poles fabricated in the works. There is, however, no difficulty in devising a technique by which poles to an almost unlimited height could be assembled and cast on the erection site. This practice is common on the Continent. In this country, we are limited by the narrowness of roads and entries to fields into which the poles have to be taken. The empirical formula developed by Mr. Ryle for the relation between the pole weight and the height and working bending moment is most interesting, and we agree with the general conclusions he has drawn.

Mr. Frost gives relative costs for concrete poles which indicate that he has considered only the shorter and lighter sizes of poles. Our experience has been that as the loading becomes heavier, the more favourable becomes the comparison between concrete and wood. We think Mr. Frost will agree that larch has given far more concern than imported red fir. E.R.A. Report Ref. F/T17 gives interesting data on this subject. As regards failure of wood poles, the paper states that failure occurs "in the region of the ground level." Brent deals with this subject in his paper (No. 154, 1935) before the Institution of Post Office Electrical Engineers on "The Telegraph Pole"; it is regrettable that the information it contains has not been made available to a wider circle. Calculations indicate that failure occurs very near ground level for stout poles up to 40 ft high, whilst a 45-ft pole should fail at $5\frac{1}{2}$ ft from the ground line.

Mr. Broadhead raises the question of foundation design, which has been much neglected in the past. A kicking block or other prepared foundation seems essential owing to the narrowness of the effective face of the pole.

In reply to Mr. McDowell, we have not experienced trouble due to the cracking of the concrete of the poles dealt with in the paper. Other types, using relatively light reinforcing, must be handled carefully.

The proposal by Mr. Falkiner Nuttall to use concrete as an insulator is interesting, but we believe that climatic conditions may prevent its development in this country.

Major Rich refers to Ciment Fondu. We used this in certain of our early experiments, but abandoned further work when aluminous cement became difficult to obtain. We have not had occasion to consider the use of twisted or notched bars, as the adhesion stresses have been well within permitted limits.

Mr. Allen makes a comparison between concrete and tubular steel poles. Apart from the question of price, the criterion for failure is different, the design load being based upon the ultimate strength and not the elastic limit of the steel.

In reply to Mr. Burke, the poles described have a strength ratio of between 2 and 3 to 1 over the normal range of heights. They are flexible in the longitudinal direction, and this offsets to a large degree their lower strength in this direction. The works cost of a square pole is very little more than that of a rectangular pole; the high field and transport costs, however, make its use uneconomic.

DISCUSSION ON
"THE HIGH-PRESSURE GAS-FILLED CABLE"*

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 18TH OCTOBER, 1943

Prof. E. W. Marchant: I am very glad to open the discussion on this paper because at the University of Liverpool Mr. E. A. Watson, in 1909, made many tests on the electric strength of compressed air (*Journal I.E.E.*, 1909, **43**, p. 113 *et seq.*), which gave the first reliable data on this subject. In his paper, Watson points out that the statement is generally made "that the dielectric strength of air is proportional to its pressure," but that actual measurements are very scanty and incomplete, covering either only low voltages or small increases of pressure above that of the atmosphere. At the end of his paper he says "compressed air as an insulation has considerable possibilities for certain cases, as it is free from viscosity and residual charge effects and is not permanently injured if it is broken down."

In the discussion on Watson's paper, I referred to the fact that the electric strength of 40 kV/mm at 15 atmospheres should make the use of compressed air as an insulating material a matter for consideration in any transmission system designed for extra high voltages. It has taken thirty-five years for the practical application of this material to be effected, but it is, I think, not inappropriate to point out that if the early observations of its properties had not been made, the cables which have now been described by the authors would never have come into existence.

I should like to emphasize the great value and importance of research into the properties of materials which may not appear to have any immediate practical utility. Very often, negative results are of value in preventing waste of energy by prosecuting research along wrong lines.

There is one fact observed by Watson which is important in connection with the possibilities of breakdown in the air spaces between layers of insulation in this type of cable. If the breakdown strength between small spheres is measured, the voltage/spacing curve is very far from a straight line. With, say, 24 000 V the sparking distance is nearly 1 in at atmospheric pressure, whereas at a pressure of only 3 atm. the breakdown distance is less than 0·1 in. The greatest trouble in making these tests was in the design of the testing equipment, because the electric strength of the compressed air was very high and even a material like ebonite, which has a very high nominal electric strength, could not stand the stress that was entailed on the insulating sleeves, when the breakdown voltage to be measured, even for comparatively short spacings, was greatly

* Paper by C. J. BEAVER and E. L. DAVEY (see 1944, 91, Part II, p. 35).

increased. The same problem has been evidently one of the most difficult tasks in the design of the compressed-gas cable, and the fact that so long an interval has elapsed before this practical cable was devised is evidence of the difficulty of the problems that have had to be solved.

I should like to emphasize the authors' statement that the problem of eliminating deteriorating influences in higher-stressed cables is fundamentally a physical one. Nearly all problems develop into physical problems, and it is the physical properties of the materials used in engineering that are of supreme importance. Too much time cannot be spent on research work intended to determine the physical properties of dielectrics. One interesting point in connection with the definition in Section 1.1 is the fact that the electric stress in the air spaces is higher than in the dielectric, so that not only does the air have to possess greater electric strength, but it has to have a greater strength than would be required if the material had the same dielectric constant as the dielectric.

It was of the greatest satisfaction to me that, before I retired from the Chair of Electrical Engineering in Liverpool University, we were able to build and equip a high-voltage laboratory specially designed for the testing of cables. That field is, I am sure, one of the most fruitful that exists to-day. To take one example, the development of television will require the production of cables with very small dielectric loss at very high frequencies. Compressed air is, of course, an ideal material for such cables, but the problem of using it for ordinary lead-in conductors is probably too difficult to solve.

Mr. H. G. Bell: A local installation of 132-kV gas-filled cable comprises approximately five miles of three single-core cables. The circuit is connected to the Grid at its two extremities, but receives a feed from a generating station through a step-up transformer at an intermediate point. Owing to the comparatively high fault that can be fed through this circuit, the provision of a sensitive protective system, which would at the same time be stable, presented some difficulty, since the 3-point arrangement renders a linear response from the equipment at the three feeding points desirable. Ultimately a development of the Translay system was adopted, and this has proved satisfactory in service.

In addition to the cable accessories described in the paper, other auxiliary equipment may be of interest. The transfer through the cable at any time is measured by an integrating watt-hour meter provided with an impulsing contact. The impulses are transmitted to the central control point and integrated over a short period, at the end of which they are transferred to an indicating dial. This equipment has the advantage that the apparatus installed in the substation is of simple well-proved design, the integrating equipment being provided at the central point. An instrument has also been installed to record the temperature of the cable core. This is actuated by means of two thermo-couples, one on the cable sheath and a second one attached to the core of a dummy length of cable carrying a current which is proportional to the main cable current. By comparing the records of this instrument with those of a recording ammeter it is hoped to obtain useful information.

Mr. P. W. Cave: The description "gas-filled" given to this cable is something of a misnomer. With the oil-filled cable, the description is literally true if the term "oil-filled" is applied to the space within the lead sheath not occupied by copper and paper. In the gas-filled cable, however, this space is occupied by both compound and gas. The authors have suggested that the term "gas-filled" should be restricted to cable made with pre-impregnated paper and gas-filled. I doubt whether this discrimination will be acceptable to advocates of other types of gas-filled cable.

The pre-impregnated cable described has a definite advantage over other types, in that the compound chosen for the impregnation of the paper can be of such a type that it will not flow on gradients. This, coupled with the fact that the cable contains practically no free compound, is important, because troubles which might result from migration of compound are eliminated.

Suggestions have been made that the factor of safety of two, adopted by the authors, could be reduced, but in my view this would be unwise.

The authors refer to the change in gas density when the cable warms up; naturally, the variation in pressure between hot and cold will be related to the amount of compound in the cable. Without compound in the cable, the rise in gas pressure from no-load to full-load would be about 13 %. If 60 % of the available space contained compound, the rise would be 20 %, and so on. It might be inferred from this that the adjustment of the amount of compound would be a matter calling for very careful consideration, but in actual practice, I presume, the adjustment becomes automatic when the sheath distends under the application of internal pressure.

I see that the authors have followed the oil-filled technique to the extent of applying a second lead sheath over the reinforcement. This second sheath has a dual purpose as it provides protection to the reinforcement from the action of corrosive agents in the soil, and also facilitates the location of a gas leak. I would like to ask the authors which of these two features is regarded by them as being the more important.

One of the authors mentioned that in carrying out a leak location the centre joint is excavated, one dome removed therefrom, and a special dome fitted. This would appear to be both difficult and unsafe to carry out with full gas pressure inside the joint. The act of removing the dome will reduce the pressure in it to that of the atmosphere, whereas the pressure within the conductor will remain at 200 lb/in^2. Is there not a tendency for this internal pressure to burst, or at any rate distort, the hand-applied insulation on the joint, and would it not be a wise precaution to switch the feeder out and reduce the gas pressure to, say, 50 lb/in^2 before attempting to find a leak?

Mr. J. Durnford: The authors have illustrated the ability of the gas-filled cable to operate satisfactorily under normal a.c. conditions, but I should like to draw attention to the conditions existing when the cable is subjected to high impulse voltages. For these, if greater than twice the normal a.c. voltage, the gas is apparently fully ionized; it follows that the stress is applied wholly to the paper insulation. I should like to know if, in consequence, effective dielectric thickness, and hence the impulse voltage strength, is materially reduced; and if it is effectively less than that of the corresponding oil-filled cable, in which the dielectric is, ideally, continuous from conductor to sheath?

Another point concerns the relative strength to over-voltage of the different items on a cable system. In the present case it seems advisable to have the breakdown strength of the joint less than that of the cable itself in order, as a last resort, to provide some degree of protection for the latter, which is more difficult and expensive to replace. Could the authors say if such a relationship yet exists for gas-filled cable systems?

Mr. D. J. Pearce: I should like further information on one point, namely how long does it take to bring the cable to its full gas pressure? Also, when is the cable subjected to the full gas pressure for the first time? Routine tests are mentioned which are carried out in the works, but they do not appear to involve the use of the full gas pressure.

Mr. W. A. Crocker: In their summary the authors state that since the economic position is sound, the gas-filled cable should be taken into consideration for schemes involving power transmission at 33 kV and upwards. Do the authors really think that the gas-filled cable is an economic proposition for 33 kV,

compared with the H-type or S.L. cable? Can they give some idea of the cost per mile for such gas-filled 33-kV cable?

So far as users are concerned, great advantages are offered by the S.L. or H-type cable—especially the former, the repair and jointing of which can be executed by the undertaking's jointers—whereas the gas-filled cable will, presumably, necessitate the services of the manufacturer's specialist. How long does it take to make a joint on the high-pressure gas cable? From my own observations it seems to take a fortnight or more, which is a distinct objection in distribution service.

What do the authors mean by the statement in Section 3.1.3 on mechanical design that "no cold-working of the pressure-retaining sheath can occur under service conditions."

In Section 3.3.2 reference is made to the use of gas-filled cable on systems using a Petersen coil. For what period would the gas-filled cable run satisfactorily with one phase of the system earthed, compared with the period of 24 hours which, I believe, is permissible generally?

The authors describe the precautions taken to obviate occlusion of air in the jointing of papers; in view of certain unsatisfactory methods of paper jointing in the past, do they think that an improvement has been effected in this respect on other types of 33-kV cable in recent years?

[The authors' reply to this discussion will be found on page 369.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 25TH OCTOBER, 1943

Mr. R. S. Orchard: In Section 7.3.1 the authors propose to test the gas pressure on site only after completing the cable route, when nearly all the joints have been buried and the detection of any leakage at joints would mean fresh excavation. This could be avoided to some extent if pressure tests were carried out on limited lengths of the route immediately after installation. Do the authors agree that such tests are desirable?

It seems important that it should be possible to gas-charge a cable to its working pressure in the minimum time. Is there any objection to raising the pressure reasonably rapidly to normal pressure, or is there a limit to the rate of rise of pressure on the cable? Some recommendations for the rate of gas-charging of cables, both initially and subsequently when the pressure has been lowered for maintenance purposes, would be interesting. As a general guide, can the authors suggest any limit to the differences in pressure allowable during charging along, say, a length of 220 yd of 66-kV 0·15 in^2 3-core cable? What maximum pressure would they use to show that there was not a complete barrier to gas flow at any point?

Is it considered that feeding arrangements are necessary only at either end of a route, or are they sometimes necessary at intermediate points? If so, can any general recommendations for the length of cable per feed point be made?

The method described for localizing gas leaks (Section 8.4) calls for excavation at the joints. Would not test connections brought to surface level with suitable valve arrangements for rapid detection be more convenient? The time factor is an important one in the case of breakdown.

Some stress/time breakdown curves for completed cables and joints on the lines of those given for the various types of paper would be useful to permit a comparison of the factors of safety available with other types of cable.

The authors strongly recommend that either a second sheath or a special anti-corrosive covering should be provided to protect the reinforcement. With oil-duct cables where a similar reinforcement of a non-ferrous type is provided, it has been found possible, where soil conditions are normal, to dispense with the second lead sheath, relying on a normal waterproof protective covering. Could similar practice be used for gas-filled cable?

According to Section 3.3.6, in future 132-kV 3-core cables the operating stresses could be considerably increased, and relative costs would then decide whether 3-core or single-core cables should be used. Presumably, if the 132-kV 3-core cable is satisfactory at the higher operating stresses, there is no reason why single-core cables and lower-voltage cables should not also operate at the higher stresses, any comparison of costs being based upon similar stress conditions for all voltages.

It is suggested in Section 7.2.1 that power factor/voltage tests should be carried out up to twice the working voltage at normal gas pressure. The gas-pressure alarms would be set at 90% of normal gas pressure and this is, therefore, a working condition. Would the authors recommend that power-factor/voltage tests should also be carried out at the alarm pressure, and can they confirm that then no ionization would occur up to twice normal voltage? This would ensure the adequate margin of safety for the Petersen-coil earthing conditions (Section 3.3).

The high-voltage test specified (Section 7.2.1) is 250 kV (a.c.) for 15 min for a 132-kV cable. This represents 3·3 times working voltage. For many years oil-duct cable designs have successfully withstood four times normal working voltage for 15 min. Could tests be made successfully up to four times working voltage for 15 min, provided the test value was not limited by the test plant available or sealing-end flashovers?

Section 7.5 gives the surge stress value of the cable as 800 kV per cm with a negative 1/50 wave. This figure results in somewhat lower breakdown figures than some suggested for oil-duct and solid cables using fully-impregnated paper. I should like to have the authors' views on the comparative surge strength of pre-impregnated and fully-impregnated paper.

It is stated in Section 3.3 that the axial stress at the core surface at the point of termination of screen depends upon the product of the radial stress at the screen and the taper of the stress buffer cone. This presumably assumes a perfect joint between the screen and the conducting material used to continue the screen across the joint. What methods would the authors use to complete this joint, since a great deal of trouble has been experienced in solid-cable joints and sealing ends in practice due to unsatisfactory design at this point?

The use of conducting tape to preserve continuity of the core screens across a 3-core 66-kV joint is recommended by the authors. Are figures available for the insulation resistance of the tape both radially and tangentially, and can the authors confirm that the tape does not affect the stress conditions at the termination of the screen?

Figures for the axial stress which the pre-impregnated paper used in the construction of the cable will withstand between paper surfaces, and similar figures for joints down the taper between the cable papers and the applied silk tape, and also across the hand-applied papers, would be useful data. Can the authors give any power-factor/voltage figures for joints alone?

Mr. E. C. I. Macdonald: Section 10 could be amplified by figures enabling the performance of the gas-filled cable to be compared with that of existing types of cable. Some information on typical ratings for gas-filled cable, based, for example, on the standard conditions used by the E.R.A. in their publication F/T128, would be of value. Does the high-pressure gas-filled cable behave very differently from other types of cable in relation to the dissipation of heat generated, and what effect do varying conditions of laying have on the current rating?

It would be interesting to know whether difficulty is experi-

enced in obtaining consistently sound brass castings for joint sleeves to withstand the severe internal gas pressure test, and whether the authors have adopted any means of reducing the number of porous rejects, and if so, whether the repaired sleeves proved satisfactory in operation.

What alloy, if any, is suggested for the lead sheaths of the cable? Do the authors favour any particular type of lead press, and are any special precautions taken in producing a pipe which will withstand the test mentioned in Section 4.3?

I fully endorse Mr. Orchard's remarks on the formidable procedure apparently necessary for locating a gas leak, and my experience of the difficulty of locating fluid leaks in other types of cable leads me to urge that much more attention should be paid to the practical side of this problem. Is it possible to leave a leaking cable in commission for a short period after the low-pressure alarm has operated, to allow the control engineer to transfer the load elsewhere?

My reading of Fig. 20 is that, provided the strand gas-pressure at the leak does not fall below 125 lb/in^2 (gauge), the region where ionization will occur is limited to a relatively small number of layers of insulation near the outer screen. Are the authors' remarks in Section 8.3 intended to convey that there is no risk of damage as a result of this ionization?

A second alarm set to operate at a feed pressure corresponding to the gas pressure at the screen below which ionization will occur at the leak, the most pessimistic conditions being, of course, selected, might be considered advisable to indicate a "circuit unsafe" condition.

Mr. A. Gray: There is nothing in the paper to describe how a cable is treated during the repair of a joint. This is a very serious matter, and, of course, applies to all terminal points. After a repair has been completed, how long will it take before the gas pressure is sufficient to re-commission the cable? I believe that, when a cable route is to be surveyed, the most suitable position for the joints should be noted and the cable should be fabricated in lengths to suit the joint positions.

Mr. E. E. Dunn: What is the approximate maximum length of gas-filled cable which can be fed from one gas feeding point? It would appear that the thickness of the gas spaces in the cable is of great importance; a strong compact reinforcement is also necessary to support the inner lead sheath against the internal pressure of 200 lb/in^2. Do either of these features impose a limitation on the bending radius of gas-filled cables? A knowledge of this radius in terms of cable diameter would be appreciated.

With regard to gas leaks, it is shown from practical experience that gas-filled cable installations can be made inherently gas-tight, but there is the possibility of leaks arising from lead-sheath corrosion due to electrolysis or stray currents. As already pointed out, it would certainly be most desirable to carry out research on a rapid method of finding gas leaks. The method of testing for gas at certain joints at successive "rings" taken from an outer sheath, is a long and costly process in the case of cables laid in concrete-surfaced roads.

As electric supply authorities are practically always joint occupiers of roadways and footpaths, the authors' views would be appreciated on the effects of nitrogen gas, from a sustained leak, percolating into cellars or the ducts and manholes of other public service undertakers.

The authors believe that, when operated under certain gas-leak conditions, a limited portion of the outer layers of the dielectric will ionize around the leak. Would such ionization produce permanent deterioration of the outer layers of the cable papers?

Some information on the relationship between gas pressure and cable surge-strength stress would be of value.

In all developments in high-voltage cables the greater simplification of installation and operation mentioned in the paper are of considerable import, in addition to lower initial cost. Operating costs incurred in the maintenance of auxiliary equipment can become very considerable on a large system.

Mr. P. Richardson: With regard to the drying of the paper in the impregnating plant it would seem that the vapour pressure of 100 atmospheres would give a temperature of about 300° C. This seems to be approaching a rather high temperature for paper. I would like to know if all the papers are laid on in the same direction, as from the layout of the apparatus a total of 100 papers are applied in one operation with the conductor rotating in one direction only. The vacuum-impregnating chamber shows a squeegee arrangement for maintaining a vacuum inside the tank; what is the order of the vacuum that is obtained?

Dr. J. C. Prescott: The successful design of the cable depends on the two facts: (1) that, as the pressure of a gas between electrodes is raised, the potential at which ionization begins is raised also; and (2) that for small electrode spacings the dielectric stress required for ionization rises as the spacing is reduced.

Working from these premises, the designers have taken what would have seemed a few years ago the revolutionary step of introducing small occlusions of gas into the cable dielectric and of subjecting the lead sheath to an internal pressure of some 200 lb/in^2. The test and service results show that their boldness has been rewarded, and we may look forward to further developments along the same lines.

Mr. J. A. Harle: Cable manufacturers carry out their high-voltage tests over 15-min periods, whereas manufacturers of other apparatus carry out 1-min tests. In view of this it is frequently difficult to assess the relative strengths of the insulation tested in the two manners when co-ordinating insulation on a system. I should like the authors to include information as to the 1-min breakdown values of the cables in relation to the working voltage or to the ionization value, as such data would be of great help in assessing whether switchgear or other apparatus is weaker or stronger than the cable.

Mr. D. Lightle: In connection with the drying and impregnation of the paper, can the authors give us some idea of the speed of the paper through the machine? It is given sometimes in connection with the ordinary drying of solid-type cables.

Mr. W. J. C. Fletcher: The authors specify that the maximum compound drainage shall be measured by heating a length of cable to 80° C continuously for 7 days, and shall not be more than 1% of the internal volume of the sheath. What is the total amount of compound, in comparison with the internal volume, which normally exists in a cable, and is not 1% a fairly large percentage of the total compound content? How does that affect the operation of the cable in a vertical position?

With regard to the gas-filling operation, either in the first instance or after repair, other speakers have asked questions about the time required for re-commissioning the repaired cable. I should like to ask whether it is considerable, especially in the first instance when all air must be expelled, and whether this has any influence on the length of cable being manufactured. Is the manufactured length of cable limited in any way by the time required for gas filling?

Nitrogen has been chosen for the gas filling, presumably because it is the most common inert gas, but do the authors consider any other inert gas as being equally suitable, apart from the question of cost, and would a gas such as helium be still better, provided it could be obtained in commercial quantities?

Mr. W. A. A. Burgess: The point that has interested me most is not directly that of the gas-filled cable, but some of the opening remarks of the authors on the question of other sorts of cables. They pointed out that there is a very considerable expansion and contraction in the normal type of cable, which switchgear manu-

facturers must provide for or put up with in cable boxes. Cable manufacturers and users show great surprise when a cable box bursts open or is found to have big voids inside it. There is always alleged to be something wrong with the design of the cable box. Mr. Davey has given a clue. A considerable expansion must be expected, and, owing to the distension of the sheath, a lowering of pressure may take place which allows the cable oil, gas or air to flow back into the cable more rapidly than a compound.

I have been very interested in the authors' very ingenious form of sealing up the cable joint boxes. Using compound in an annulus upside down to be melted when in position and then running down to seal the flanged joint is not very convincing. I do not believe that a thermoplastic, such as compound, will withstand gas pressure indefinitely when run that way.

[The authors' reply to this discussion will be found on page 369.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 1ST NOVEMBER, 1943

Mr. G. S. Buckingham: I have prophesied for a long time that the solid-type 33-kV cable would soon be out of date. I am sure there will be a very great expansion of high-voltage networks after the war and that they will very largely be installed with some form of ionization-proof cable.

The authors have described several gas-filled cable installations in this country and abroad. Doubtless there would have been many more in the absence of the oil-filled type of cable, which has proved itself over many years to be free from ionization troubles at all working voltages. There are two stages in the development of a new design of cable. The first relates to the theoretical design, manufacture and testing of the new cable in short lengths. The second stage, and perhaps the more difficult, relates to the laying, jointing, putting into service and maintaining in service of the cable in the field. The oil-filled cable may be said to have passed through both stages: the gas-filled cable has passed through the first, but is still passing through the second.

The method of locating possible gas leaks leaves a good deal to be desired. I think that the necessity to dig down to buried joint-boxes for making gas-flow tests could be obviated by the use of a simple device installed inside the joint which could, by the aid of a pilot cable laid alongside the main cable, give an immediate indication of the gas leak to the nearest joint position. I should be grateful if the authors could indicate the precautions which must be taken in mounting the sealing end shown in Fig. 11 in order to overcome the end-thrust produced by the high gas-pressure in the cable.

(*Communicated*): The figures given for the resistance to gas flow along the cable seem to be very high. Using the most favourable figures given in Section 8.3, it seems that the time taken to charge up a length of 6 miles of 132-kV cable, even when fed with gas from both ends, would be at least 4 days. If this is so, it means that if a leak, large enough to reduce the gas pressure at the lead sheath to zero, were to develop near the middle of the cable length, the resistance to flow of gas from the terminal feed-points would be so great that a leak would be undiscovered for days or even weeks before the pressure in the gas cylinders had dropped sufficiently low to operate the alarm system. During that time ionization would be going on, and breakdown would inevitably follow. It seems to me that if these figures are correct the authors may be compelled to sectionalize their gas-feed positions by means of stop joints, or alternatively, provide much larger gas channels, which might take the form of a hollow conductor such as is used on the higher-voltage oil-filled cables. Either of these alternatives will entirely cancel out any advantage the gas-filled cable may have over the oil-filled cable and still leave it with the considerable disadvantage of a very high internal pressure to be restrained within a lead sheath.

Mr. D. P. Sayers: There are some 15 route miles of 33-kV gas-filled cable of the type mentioned in the paper in commercial use on the Sheffield system, of which the first section has been in service for about four years. The choice of this particular type of cable was primarily one of economics. The Sheffield system is dense and compact, with high short-circuit capacities and relatively short cable lengths. On some feeders the switchgear costs, amounting to some £10 000 per panel, exceeded the cable costs. Previously, the standard practice has been to use 0·3-in^2 solid-type cable with a rating of 20 MVA laid direct, or 16 MVA laid in ducts, and it was clear that with a larger cable rating the switchgear cost per circuit and the total cost per kVA transmitted could be reduced.

In 1936, the possibility of a larger-capacity cable was explored and the design finally accepted was a 0·4-in^2 gas-filled cable with a dielectric thickness of 175 mils and a gas pressure of 100 lb/in^2. This cable has a thermal rating of 27 MVA laid direct, an overall diameter of $3\frac{3}{4}$ in, and a weight of 53 lb/yd. The same rating with solid-type cable would require about 0·6 in^2, with an overall diameter of more than $4\frac{1}{2}$ in and a weight of 70 lb/yd. The price per kVA rating would be 20% more than for the gas-filled type.

Whilst the installation has not been devoid of trouble, experience up to date has done nothing to shake my confidence in the gas-pressure cable; and, if the choice had to be repeated to-day under similar circumstances, I should select the same type of cable. Oil-filled cable could have been supplied for the same thermal rating, but the extremely hilly nature of the terrain and the consequent problem of fluid-pressure control were serious handicaps.

I am disappointed to find very little reference in the paper to the cost of gas-filled cables. The basic manufacturing costs ought to be substantially lower than for the solid-type cable of equivalent rating.

While the technique of the gas-filled cable is a sound and scientific approach to the problem of ionization control, the presence of high mechanical pressure, in addition to high voltage, calls for more exacting standards of quality control in manufacture and installation, and unless adequate steps are taken to avoid minor imperfections, which may have far-reaching consequences, the gas-filled cable will inevitably suffer breakdowns and acquire a bad reputation.

Will the authors say why they fill the joints with compound, as the complicated arrangement of gas pipes in the initial installations has proved very liable to choking. Surely there is no need for compound filling of the joints, provided that the cores are adequately spaced and supported mechanically.

Mr. C. Kibblewhite: The authors have emphasized the difference between the gas-filled cable and other forms in which gas is employed for the suppression of ionization. One of the principal differences lies in the nature of the dielectric of the gas-filled cable, which embodies numerous gas spaces. A dielectric of this type is naturally predisposed to ionization and could not survive high working stresses if the gas occluded in the spaces were not under pressure. It is therefore very important to know what margin of safety against ionization has been provided in this design of cable. The authors have recorded the results of power-factor/voltage tests at voltages up to twice the working voltage, but I do not think these demonstrate a sufficient margin of safety. Have power-factor/voltage tests

on the gas-filled cable been carried out at higher voltages, and if so, at what voltage does ionization set in?

To my mind, a dielectric embodying gas spaces is at a disadvantage as compared with a fully-impregnated dielectric, and the proper and logical approach to the design of a gas-pressure cable is to provide it with a dielectric as near perfect as possible and to use gas under pressure to maintain this dielectric without deterioration under working conditions. This principle has been adopted in the design of the impregnated gas-pressure cable, which, unlike the cable described by the authors, has a fully-impregnated dielectric. This cable has been the subject of very careful research and thorough testing, which indicates that ionization is excluded up to at least four times its working voltage, and several examples have given very satisfactory service in commercial operation.

Mr. D. T. Hollingsworth: Three types of dielectric have been used in pressure cables: (*a*) dry paper dielectric, (*b*) semi-impregnated paper dielectric, and (*c*) fully-impregnated paper dielectric. The authors describe a semi-impregnated dielectric with gaps between the turns of the paper, presumably to obtain pressure communication with the centre of the dielectric. A disadvantage of this arrangement is that the ionization voltage, which is a measure of the safety factor, is only about twice the working voltage of the cable. In the fully-impregnated dielectric, which has an ionization voltage of at least four times the working voltage of the cable, no gaps are left between turns, the pressure being communicated to the centre of the dielectric by the viscous compound with which the dielectric is impregnated.

The main advantage of the dielectric described by the authors appears to be that there is less possibility of the cable compound moving in the dielectric when the cable is laid sloping. Very severe tests have been carried out on fully-impregnated dielectrics, and commercial installations have been completed with cables erected in a vertical position over a considerable distance. No movement of the compound capable of affecting the characteristics or satisfactory operation of the cable has occurred. It is questionable, therefore, whether the advantages offered by the authors' dielectric are worth the associated reduction in ionization voltage.

Mr. T. H. Varcoe: The Germans developed a form of gas-pressure cable some ten years ago. I believe the Hochstädter company installed several miles of this type of cable in Holland, Denmark and Germany.

It would be of interest if the authors would give their opinion of the practical application of this type of cable, and of the respective merits of the different designs of gas-pressure cables.

Mr. F. W. Hayes: With a cable of this type, the user would like to know whether, if there is a leakage of gas, he can continue to keep the affected section of the line in circuit, as I believe can be done with an oil-filled cable, because continuity of supply with regard to the large undertakings is absolutely essential.

Mr. D. Kingsbury: The possibility of compound stopping up the small pipes used for carrying over the gas supply has been mentioned. In my limited experience with gas-filled cables, this quite inexplicable ingress of compound has been found a very great nuisance. In theory the compound should not migrate, but it does actually travel several feet upwards.

In the type of sealing end shown in Fig. 11 there appears to be no venting of the space between the inner and outer porcelains, so that with any small leakage from the inner porcelain, pressure cannot be relieved to prevent ultimate rupture of the outer porcelain.

Is there any possibility of eliminating the complications inherent in using nitrogen at a pressure of 200 lb/in^2 in a cable, by introducing a much denser gas, such as Freon 12 (CCl_2F_2), at or about atmospheric pressure?

Mr. N. Care (*communicated*): The method of gas-leak location given in the paper appears to be very cumbersome. With a cable 12 miles long, the location and repair of a gas leak might take days or even weeks, involving excavation of ground, the opening of six joints, further excavation, and cutting the outer cable sheath at numerous places. This would be a very serious matter on a large transmission system where a 132-kV cable might normally be carrying a load of 50–100 MVA. Have the authors any proposals to put forward which would simplify the method of localizing gas leaks?

Some improvement could be achieved by bringing the gas cross-feed pipes out of the joints to inspection chambers and installing a simple system of gas valves, so that readings could be obtained on a differential gauge without the necessity of excavating ground and opening up the joints. In congested streets where any cable is very liable to mechanical damage, there would be no means of ascertaining if the outer sheath of a gas-filled cable was fractured until a gas leak occurred following corrosion of the reinforcing tapes of the inner sheath a long time after the original damage occurred.

Is it necessary to maintain the cable under reduced gas pressure when carrying out jointing operations? If not, is there a possibility of moisture being drawn into the cable by a "breathing" action resulting from temperature changes?

I agree with the authors that the final decision regarding the choice of the type of cable is largely a question of economics. Could they give any information regarding the cost per kVA of carrying capacity for gas-filled cables for a working voltage of 132 kV, and state how this cost varies with the cross-sectional area of the conductor?

I should also like to have figures giving the dielectric loss at varying conductor temperatures for this type of cable. It is noted in the paper that the maximum conductor temperature under service conditions is 85° C. Is this the maximum temperature under which the cable can be safely operated, or may an increase in conductor temperature be allowed to provide for overload rating?

Mr. A. C. MacQueen (*communicated*): The gas spaces in the dielectric of the gas-filled cable, and the increase in the ratio of gas space to compound space thus obtained, appear to have the disadvantage of reducing the gas density at the conductor surface at comparatively high temperatures, with a resultant reduction in the ionization stress and in the factor of safety of the cable. There may also be a reduction in the carrying capacity of the cable due to a lower permissible operating temperature.

The authors stress that there is no movement of impregnating compound in the gas-filled cable. Do they consider that the migration of compound in a cable would seriously impede the flow of gas? If not, would the presence of a certain amount of free compound in the dielectric have any serious disadvantages? Would not gas replace compound in the spaces created by migration?

In Section 3.3.3 the authors point out that impregnated-paper dielectric has a higher electric strength than dry-paper dielectric and withstands surge voltages better. Does the presence of gas spaces in the gas-filled cable, and the absence of any free compound, reduce the electric strength and the ability of the cable to withstand surge voltages? A second cable sheath is recommended. This appears to be an expensive method of providing protection against chemical action. Would not suitably-treated tapes be sufficient?

Only single-core cables for a working voltage of 132 kV are mentioned. Are 3-core cables for this voltage likely to be available in the near future at an economic price?

I should like information regarding the type of compound used

in the joints. Do the authors consider that the use of silk-tape lappings in the crutch of a 3-core cable forms an effective seal against the migration of semi-fluid compound?

In the case of a gas leak the alarm is set to operate at 180 lb/in^2. The pressure in the cable varies from 200 to 245 lb/in^2. Are any arrangements made to compensate for this variation in pressure, or will any serious reduction in gas density occur before the alarm operates if the cable is carrying full load? This question of reduction in gas density under gas-leak conditions also appears to affect the curves given in Fig. 20. If these curves correspond to a temperature of 15° C, then at maximum service temperature the point of intersection of the curve "Gas Pressure to Suppress Ionization" and the curve "Radial Gas Pressure at Leak" appears to be considerably higher and the "Region where Ionization will Occur" will be much larger. In view of this, are the authors satisfied that a sufficient margin of safety has been allowed in the design of the cable, and are any difficulties likely to occur during manufacture which would affect this margin?

[The authors' reply to this discussion will be found on page 369.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 6TH NOVEMBER, 1943

Dr. J. L. Miller: A most important feature of the gas-filled cable is the fact that, because it contains no free compound, the question of compound migration does not arise. There is thus no need for barrier joints or other devices to prevent migration, and there is no danger that succeeding load cycles will cause alteration to the value of the thermal resistivity at the highest points of the route. I therefore wonder whether—even at fairly low voltages where the case for the gas-filled cable as compared with solid cable is not necessarily strong—it might not be advantageous, simple and economical to install the former in sections where route conditions are hilly. Have the authors given consideration to this point?

Another excellent feature is that the permittivity of the gas-filled-cable dielectric is low—generally of the order of 2·8, according to my own measurements. This figure is certainly lower than that applicable to other types of dielectric and has obvious advantages where long lengths of cable are involved.

The authors describe very fully the rigorous testing which they have applied to their cable, but they have said nothing about high-voltage a.c. type tests. As they show, and I agree with them, the power-factor/voltage relationship is flat until the ionization point is reached (about 2 to 2·5 times the working voltage), when the curve bends upwards rapidly. Thus, by design the cable is then ionizing vigorously, and in this range it would appear entirely fortuitous whether the cable would break down in the normal time of 15 min applicable to such a test, It seems wrong, therefore, to subject the cable to a voltage test which is very much above the normal ionization limit, and I should like to have the authors' views on this point. In raising the matter I would also point out that it must not be confused with the behaviour of the gas-filled cable under the influence of high-voltage impulses; here conditions are totally different and, as I have remarked in the London discussion, the gas-filled cable has a satisfactory impulse strength.

Previously the authors have laid emphasis on the use of ribbed or embossed paper. This paper had two advantages, particularly for the higher-voltage designs. One advantage was that the electric strength was a little higher than that of ordinary paper. The other was that it allowed permittivity grading to be incorporated in the design, a feature, incidentally, that was dealt with by Mr. Beaver in his 1914 paper on cables. I presume that the authors are still investigating the point, as it will be most interesting to hear how the idea works out in practice.

Finally, it is perhaps not inappropriate very briefly to consider future trends. The gas-filled cable is now accepted and will therefore stay with us for a long time to come, but as time goes on one naturally feels certain that further developments will take place both in regard to the gas-filled cable and to other types of gas cable. Possibly one change will be the use of dielectrically-stronger paper and gases having characteristics better than those of nitrogen. The next step may be the incorporation of synthetic materials with suitable impregnating media, the synthetic material being extruded or in tape or string form. Then, one day there might be a swing right over to the other extreme, so that instead of cables operating at a pressure of 200 lb/in^2, a high-vacuum and possibly continuously-evacuated cable, having a minimum of solid dielectric, might be achieved. It would be interesting to have the authors' views on this point.

[Dr. Miller then referred to several other points relating to the design of the cable that are covered by his contribution to the discussion in London.]*

Dr. J. M. Meek: The curves of Fig. 3 for the voltage gradient required to cause onset of ionization show that this gradient increases by about 5·5 times when the gas pressure is raised from 1 atmosphere to 200 lb/in^2. This is not as large an increase in gradient as that obtained for the same gap length between metal electrodes, where, for the same change in gas pressure, the breakdown voltage increases by about 7·5 times. However, it is probable that the onset of ionization is not altogether governed by the breakdown of a layer of gas, of thickness equal to the radial depth of the void, but rather by the surface sparkover across the edge of the void, and it is known that the sparkover voltage across surfaces does not increase as rapidly with increasing gas pressure as that for the gas alone. It might be of interest to make comparative tests with d.c. and a.c., to ascertain whether any difference exists between the corresponding ionization onset voltages for both high and low gas pressures, on account of the formation of space charges in the voids. This space-charge formation tends to lower the stress in the void and minimizes ionization for a constant d.c. field, but when the field is alternating a considerably greater degree of ionization takes place because of the continuous cancellation of this space charge on field reversal. Such an effect is known to have a marked influence on the breakdown of impregnated cables, where the voltage gradient required to cause breakdown with direct current is appreciably higher than that with alternating current.

The presence of space charges also gives rise to a mechanical force which attracts the opposite sides of the void. Calculations would appear to indicate that, for the smaller voids, this force may be of the order of several lb/in^2 at the onset of ionization and I should be interested to know whether this effect is thought to be at all important in accelerating breakdown.

The authors have not made reference in their paper to the use of cables with gases at low pressures, where the product of pressure times radial gap in the void is below that corresponding to the Paschen minimum in the breakdown-voltage curve for the gas. This minimum occurs in nitrogen at a pressure of 150 mm Hg for a 1·75-mil gap and, with further reduction in pressure, the breakdown voltage gradient increases until, at about 20 mm Hg, it is approximately the same as that obtained by the authors with a pressure of 200 lb/in^2. This breakdown gradient at low pressures, however, is that obtained under ideal conditions, and it is probable that a lower pressure than 20 mm Hg is required

* See 1944, 91, Part II, p. 53.

to give satisfactory operation in the practical case. As low-gas-pressure cables might appear to have some advantages over high-gas-pressure cables, the authors' criticisms of the former would be valuable.

Mr. W. H. Duncan: As a user, I would pay tribute to the stability of present-day 33-kV cables, of which there is a route length of 150 miles installed on the undertaking with which I am connected. During the last five years we have had nine faults, less than two faults per annum. Two of these faults were on belted-type cable laid some 20 years ago and of these one only was due to deterioration of dielectric. I have had several opportunities recently of examining the condition of the dielectric of cables installed about 15 years ago, and in no case was any sign of deterioration discernible. It is therefore my opinion that 33-kV cables are now as reliable as 6 000-volt cables were, say, 30 years ago.

The authors do not give a comparison of the cost of installing gas-filled cables as compared with that for cables of the solid type and, apart from their use on gradients or in vertical positions, it seems that unless a very good case can be made on economic grounds for these cables, there is little scope for their use at 33-kV pressure; particularly is this so where questions appertaining to parallel running are involved.

The authors are to be congratulated in putting forward a cable which should have a field of service at the higher pressures of 66 kV and 132 kV and, it may be, at even higher pressures. The comparative absence of auxiliaries, necessary on some other types of cable, is a welcome feature of the gas-filled cable. Those who have had experience of the difficulties of finding room for such auxiliaries as are needed on some types of extra-high-voltage cable will welcome the authors' proposals, backed by their statement, as to the reliability of their products.

One or two points in the design of gas-filled cable merit attention. One is that on multicore cable, above the first lead sheath there are apparently seven metallic layers. It seems that if the integrity of the outer lead sheath is not fully maintained and moisture obtains access, there are elements which may set up galvanic action with possible corrosion. Another point is: What effect would the closure of gas-filled spaces in the dielectric have in positions where the cable is subjected to heavy handling on difficult routes? Also, would the authors state the approximate weight per yard of 0·3-in^2 3-core 33-kV cable, and also what maximum drum length of cable can be manufactured?

The paper indicates that progress in the manufacture of cables for super-voltages is being maintained. The efforts of manufacturers to produce cables to meet all requirements is laudable, and the gas-filled cable seems to be a step in the right direction.

Mr. W. Szwander: A prospective user of cables rated for 66-kV or more has to make his choice between the oil-filled and the various types of gas-filled and compression cables. This choice is rather difficult at present: though the gas-filled cables appear to be in many respects superior to the oil-filled cables, there are yet points in their design which may give rise to some fears as to their performance over longer periods, such as stability of paper and of oil or of compound in strong electric fields, in direct contact with compressed gas, and the performance of the reinforced sheaths with the high internal pressure of 200 lb/in^2. The great difference between the two types of cables consists at present in the amount of practical experience with them. There are not much less than 1 000 miles route-length of oil-filled cables in operation, some of them for nearly 15 years. To the best of my knowledge, there are not more than some 50 miles of gas-filled and compression-type cables installed, and experience with them extends to only 6–8 years. Thus the oil-filled cable is already an approved industrial application, whereas the gas-filled cable is still in its initial stage of development.

Support of this view is furnished by the technical literature (e.g. by the papers of G. B. Shanklin, *Transactions of the American Institute of Electrical Engineers*), where it can be seen how designers of gas-filled cables hold different opinions, even on such fundamental matters as the pressure value, the use of strand-shielding, the thickness of paper tapes, and the use of lead sheath or steel pipe, etc. In contrast to this, the oil-filled cable seems to have already attained a more or less standardized design. No definite judgment of the economic aspect of the cable-type described in the paper is possible, without data of the cost of complete installation, as compared with oil-filled cables for 66 and 132 kV and solid-type cables for 33 kV; such data are unfortunately missing from the paper.

It seems that the high gas-pressure used may be the main source of troubles on longer operation (no quick-ageing stability tests can completely simulate actual operational conditions), and this is definitely a factor which considerably increases the cost. Is it really necessary to use as high a pressure as 200 lb/in^2? All the advantages in comparison with solid-type and oil-filled cables could apparently be achieved in gas-filled cables with pressures as low as 15–35 lb/in^2. Higher pressures merely allow a further reduction in insulation thickness, such reduction being limited by the requirements of impulse strength, and any resulting economies are offset by an increase in cost of the sheath reinforcements. Particularly for voltages of 33 and 66 kV, the gas-filled cable with 200 lb/in^2 gas pressure does not appear competitive with other cable types.

It is surprising to find that there is a fundamental difference between the authors' data in Fig. 3 and the corresponding ionization figures given by Shanklin (in his data the ionization stress at 200 lb/in^2 is about 80 kV/cm). I should be obliged for a comment on this point, as this represents, after all, the design basis of the gas-filled cable.

Could the authors also give information on how their type of cable compares with solid-type and oil-filled cables, in respect of the thermal time-constant which is decisive for the overload capacity of cables?

Mr. F. Linley: To those concerned mainly with the practical aspects of cable use, the very simple construction of the authors' cable and its freedom from external complication will be noted with satisfaction. If the cable justifies the authors' claim that it will work satisfactorily up to 264 kV, mains engineers will owe them a heavy debt.

The authors state that the lower the gas pressure within the voids formed as a result of a temperature cycle, then the more susceptible they will become to ionization. Surely this statement should be considerably qualified, as when considering vacuous spaces it is found that the harder the vacuum the higher the dielectric strength of the void. Further information is desirable on the mechanics of void shapes in the cable after it has been subjected to bending and after such control of the careful positioning of the voids in the dielectric, which they have when it is being manufactured, has been lost, as well as on the effect of creasing and wrinkling of the paper which are unavoidable.

In 1939, in Paris, the authors advocated ribbed paper for the control of the gas spaces. Has this been found to be unsatisfactory, as it is not embodied in the present paper? Do any of the existing installations incorporate this type of paper? Its elimination is to be welcomed, for it is most undesirable that the safety of transmission should depend on the permanent wrinkling of a paper strip.

The emphasis laid on the necessity for the correct design of stress buffers at the screen termination of the cable deserves unqualified approval, as the importance of this feature is not always fully appreciated. Do the authors consider it possible that, after the joints have been installed for a long time, the holes leading

to the gas-transfer pipes from side to side may become choked by the high-viscosity compound used in the joint? It is appreciated that the crutches of the joints are taped and should not leak, but such mishaps occur even in the best-designed systems. Should the transfer pipe from side to side become clogged and gas leaks occur further down the line, the results would be serious.

How is it ascertained that the air has been completely expelled from the cable when the gas has been introduced in the factory? If, because of maintenance or some other reason, one of the centre joints of, say, 10 miles of cable has to be dismantled and remade, it would apparently be difficult to make sure that all the air had been removed from the adjacent cable after completion of the work.

Mr. H. G. Bell: The demand for cables working at higher pressures has increased considerably in recent years, partly owing to the increase in loads generally and the resulting necessity of handling large amounts of power in very restricted spaces. In considering the use of high-voltage cables as against the use of overhead lines the special properties of cables require consideration.

In the early days of the Grid the capacity of the overhead lines occasionally caused trouble in connection with voltage control, but with the growth of load this difficulty has largely disappeared. Any extension or replacement of the Grid by high-voltage cables would introduce problems due to the high charging current of the cables, and some means of compensating for this charging current would then certainly be necessary.

The second factor of importance is the low reactance of cables as compared with overhead lines. In the operation of an extensive interconnected system, the reactance of overhead lines is a most important factor in limiting the rupturing duty to which switchgear at any point may be exposed. When cable of practically negligible reactance is used to interconnect large load centres, the level of fault at each centre will be materially increased. In one local instance, where a length of 132-kV cable has been installed, it will almost certainly be necessary to insert artificial reactance in the cable circuit for this reason.

I have no doubt that the manufacturers of high-voltage cables are capable of producing a perfectly sound and trouble-free cable. If any trouble is experienced in practice it will almost certainly be due to joint and other accessories, and particular attention should be paid to the various accessories upon which the continued satisfactory operation of the main gear so materially depends.

Mr. H. Shackleton: In Section 3.3.2, movement of and mechanical stress on the papers during bending of the cable are stated to be proportional to the distance from the cable centre. Would it not have been more correct to say that movement and stress are proportional to distance from the cable centre multiplied by the cosine of the angle between the plane containing the axis of the bent cable and a diameter through the point under consideration? Clearly movement and stress are greatest at the inside and outside of the bend, and least on a diameter at right angles to the plane in which the cable is bent.

In Section 4.2.1 it is stated that any defects in the raw roll of paper can be seen by the machine operator. The use of some form of photo-electric or other scanning device to operate an alarm in the event of a defect being traced, would appear to have many advantages over the present method.

From time to time a certain amount of difficulty has been experienced in installing the larger 3-core S.L. solid-type cables, and it is unlikely that the reinforcing tapes of the gas-filled cable will facilitate handling (4.5).

Location of gas leaks (8.4) appears to be slow and costly. Loss of gas pressure may result in electrical damage so that an electrical fault, in addition to a gas leak, may have to be located. Fortunately, the two faults will probably be fairly close together.

After repair of a fault involving gas leakage or electrical breakdown or both, it would appear to be necessary, first of all, to test all cable for gas leaks. A similar test after installation is carried out at 250 lb/in^2 and extends over two days. Finally, a voltage test is required. The time taken to locate a fault and carry out necessary repairs and tests will be appreciably longer than for solid-type cables.

Mr. H. Allcock: The authors' leadership in this particular field of engineering directs attention to three main features. In the first place, their gas-filled cable with its reinforced sheathing is a product finished in the factory under scientific control at all stages of manufacture, without any reliance being placed on its further protection during installation. Secondly, no external equipment, such as oil reservoirs, are required, and, thirdly, there is no migration of the impregnating compound from the higher to the lower levels of the cable route. There is consequently no need to provide special barrier joints.

It must be nearly 50 years since Mr. Beaver introduced his method of impregnating cable papers, and this further application of the same method is especially noteworthy. Attention has already been drawn to the pioneer installation of long lengths of vertical-shaft cables which have been in satisfactory operation at 22 kV for many years in South African gold mines without any evidence of migrating compound.

Mr. H. L. Partington: The authors' design of straight-through joint in which the whole of the insulation is under compression, thereby reducing any tendency to ionization, is superior to contemporary designs for solid-type cable. It does not appear, however, to provide positive gas-filling of the joint insulation; for, while the inner surface of the applied insulation is in contact with the gas-filled conductor, the outer surface is sealed off by compound, and it is difficult to appreciate how the occluded air in the applied insulation is dispersed. What are the authors' conclusions as to the desirability of extending the gas-filled dielectric technique to the joints? Regarding the use of silk tapes in conjunction with paper tapes, for homogeneous joint insulation it would appear preferable to use paper throughout.

Mr. J. H. Pirie: To illustrate one situation in which a gas-filled cable may be installed, Fig. A shows part of a cable route covering

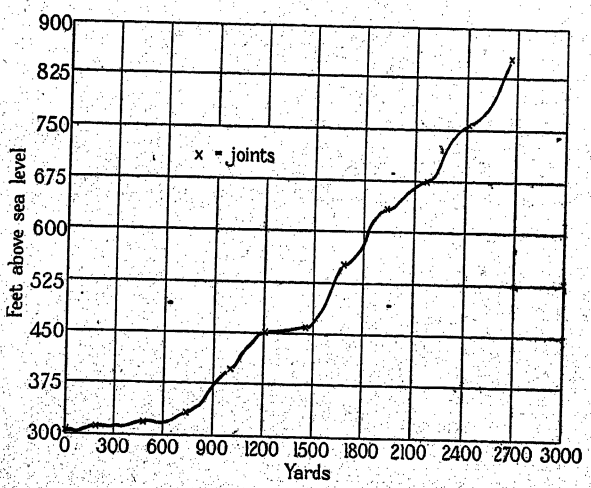


Fig. A

a distance of 2 660 yd and a difference in level of 530 ft. No specially-designed fittings, such as barrier stop-joints or reservoirs, are required, the standard form of joint being used throughout. This installation has now been in service for about 5 years.

[The authors' reply to this discussion will be found on page 369.]

SHEFFIELD SUB-CENTRE, AT SHEFFIELD, 15TH DECEMBER, 1943

Mr. A. Ledsom: In Sheffield we have a considerable length of gas-filled cable installed on our primary system. No difficulties have been experienced in the handling of this type of cable, since the drums are delivered without reservoirs or other attachments; nor has there been difficulty in the installation of the cable, whether it be on concrete posts, laid direct or drawn into conduits. In fact, we have had less difficulty installing gas-filled cable than the solid dielectric type, as there is less weight for a similar capacity and the cable is more flexible.

No greater care is required when jointing gas-filled cables than with other types, since at all times the maximum care must be exercised when jointing high-voltage cables, but our experience has been that an extra day and a half must be allowed. This is due, in a large measure, to the extra taping which this type of joint demands. I should like to ask if, on account of the time spent in wrapping the paper and silk tapes round the conductors, there is any risk of moisture being transferred from the jointers' hands to these tapes? Also, is there any possibility of our realizing an ideal gas-filled joint in which the compound and tapes can be entirely dispensed with?

If the lead sheathing of the cable were to be pierced, the amount of labour required to locate the gas leak would be considerable. The ground has first to be opened at each of the selected gas-pressure testing points and then trenches excavated until the puncture is revealed. I suggest that, when the faulty cable section has been cut out, half joints of the barrier type be made on the ends of the assumed sound sections and the sections gassed up. This method would prove whether the gas leak located was the only gas leak on the feeder. The remaining halves of the joints would be completed after the replacement length of cable had been installed. When testing, it is essential for the gas to be passed from one end of the cable only, to make certain that there are no obstructions to the gas flow throughout the entire length.

Mr. B. Calvert: Little space has been devoted in the paper to gas-leak location, but once the cable is installed, a distribution engineer's main worry is the possibility of breakdown, and the job of locating a leak is a lengthy one. The excavation and cleaning of joints, and the fitting of test domes and gauges, take a considerable time, and waiting periods are necessary for gas conditions to settle after loss of gas in performing some of these operations. Further delay is caused in transferring test gauges from joint to joint. It appears that the process could be speeded up in various ways, for example, by using three gauges simultaneously. Care must be taken on very small leaks as readings may be affected by temperature changes or gas blockages in joints.

The method described locates the leak to a length between the joints. I should like some information on the technique of checking for gas emission with a two-sheath cable, and the apparatus used for applying gas pressures between the two sheaths. With a single-sheath cable, the trench between joints is flooded to detect the leak. This may be simple enough on level ground, but there are obvious difficulties on inclines. Have the authors any other method to offer for single-sheath cables?

If the leak is large a location may be possible by observations of the pressure gauges at each end of the cable. I have carried out an experiment on a length of 3-core cable, which I should like to describe. Taking a length AB (Fig. B) of the cable and allowing gas to escape rapidly at the point X, the pressures at each end of the cable will fall at different rates. The curve A refers to end A of the cable where the pressure falls more rapidly since it is nearer the leak. The portion CDE of the curve is the time during which the gas is adjusting itself to the pressure curve shown in Fig. 19 of the Paper. This must be ignored

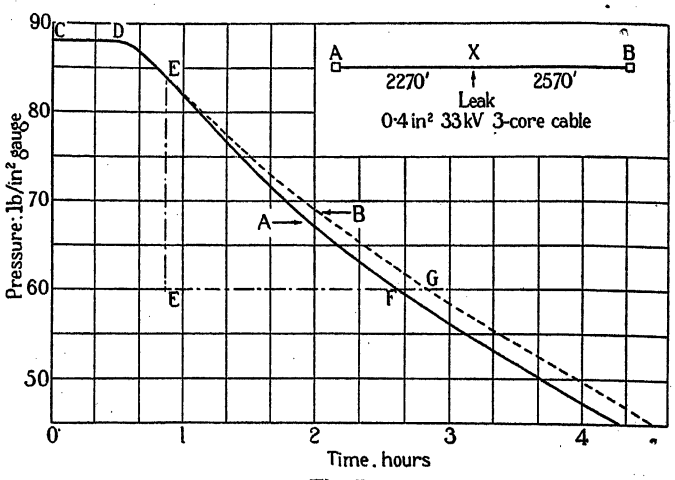


Fig. B

and the point E taken as the commencement of pressure fall. If now we take, say, a pressure of 60 lb/in^2 on the curves, then the ratio E′F/E′G is approximately equal to AX/XB in this particular case. Further tests with different speeds and positions of gas leak are required, however, to find if there is any value in the idea. Have the authors carried out such a series of tests on a completed installation, for every effort should be made to improve the methods of leak location?

Mr. H. R. Mabbott: What length of this type of cable is in service in this country? In the district in which I am interested, the route length is approximately eight miles. Sheffield has, I understand, more than this. From the route length given in the paper, it would appear that there is only a small mileage outside Sheffield and North Derbyshire. Can the authors account for the small amount of this cable in this country?

From the remarks of earlier speakers, our experiences are on very parallel lines. After some years of usage, I consider this type of cable to offer a good and reliable transmission medium.

The previous speakers have mentioned the trouble occasioned by the gas leak. To my mind, this might be termed a very desirable form of trouble, compared with that of insulation failure. Can the authors confirm that there has been no case of insulation failure on a gas-filled cable? If we have really got rid of our electrical failures and all that follows in their train, then I feel we have taken a big step forward.

The gas leak tends to be treated as a serious emergency and, in consequence, pressures are immediately disturbed by the removal of domes or the injection of gas. This often completely seals up the leak. In a cable of this type, it is important that the location of a leak should be possible without disturbing the conditions inside the cables. To do this, I suggest that manholes should be fitted over each joint, giving access to robust valve gear which would control each length and also the cross flow.

In Derbyshire we have rather unusual contours for cable routes. One cable rises 500 ft in approximately one mile, and I suggest that no other type of cable would give such satisfactory results under these conditions.

Mr. R. M. Longman: In this area, the Central Electricity Board have five short lengths of 66-kV cable, somewhat similar in type to that discussed by the authors. The main points to be considered are: (*a*) what reasons are there to justify the additional cost of such cables, and are they capable of being operated at higher current densities, i.e. greater kVA loading; and (*b*) what is the liability to damage and the cost in money and idle time necessary to effect repairs?

If cables of any new experimental types are to be thoroughly tried out, they should be installed in positions where they can be regularly subjected to both heavy and light loading periods. All cables, however carefully laid, may be subject to mechanical damage from external damage. Have instances of such damage actually occurred and, if so, what was the nature and extent of the damage and the time necessary to complete repairs and to put the cable again in full commission? This is surely a vital point. Much has been said about gas leaks. How long can a gas leak exist and how low can the gas pressure drop without endangering the cable as a whole? How can small leaks be detected? Has a cable actually failed whilst in service entirely owing to a gas leak and loss of pressure?

Mr. W. E. B. Nettleton: The termination of a gas-filled cable in switchgear presents difficulties, and an alternative method adopted at Sheffield is to terminate the gas-filled cable in a barrier joint of the type shown in Fig. 13. The three solid single-core cable-tails from the barrier joint are then connected to the switchgear in the usual way. The gas equipment is simple and similar to that described in the paper, except that there is an additional pressure gauge which is connected to the solid side of the barrier joint to give warning of any gas leakage across the joint. The equipment is inspected weekly, and the gas pressures recorded. By this means a check is kept on the gas-pressure system and any alteration is quickly noted. If the gas equipment is erected in a gas pillar out of doors, it is advisable to provide some heating, otherwise the damp atmosphere may cause the gauge pointers to stick, the gauges then giving unreliable readings. It has been found a distinct advantage to erect the gas equipment inside a warm switch-room. Another improvement has been the fitting of cap nuts on all the valves to prevent gas leakages via the valve stems.

Regarding the American scheme described in the paper, can the authors say what precautions are taken to protect the cable cores when pulling them into the steel pipe, and also what precautions are taken to support the cores in the pipe against stresses due to short circuit?

Mr. A. Haddock: A previous speaker has pointed out that gas-filled cable can be laid without special precautions on routes which include steep contours, but solid-type cable made by the same manufacturer is already suitable for such contours without special precautions. The advantages which led to the choice, in 1938, of gas-filled cable for transmission of large blocks of load at 33 kV from generating stations to city centres were economic ones. With 33-kV solid-type cable, previously used, 0·30-in^2 3-core had been regarded as an upper limit in size for physical reasons. This cable has a rating of 15 MVA and as the distances were short, switchgear costs tended to be high (20% to 40%) relative to feeder costs.

A 0·40-in^2 3-core gas-filled cable is no larger overall than 0·30-in^2 3-core solid cable, and has a rating of 27 MVA. Its adoption effected a saving in switchgear costs per kVA and also a slight saving in cable costs per kVA. Eight feeders, totalling 14·55 miles are now in commission in Sheffield, all of the single lead-sheath type. I agree that the later type with the two lead sheaths should be standardized for future use.

Much has been said about gas leaks and it has been suggested that this point has been over-emphasized. I cannot agree. Operating experience in Sheffield has not included an electrical service breakdown, but has emphasized the need for improvement in gas-leak location and procedure generally. I prefer the advance warning given by a gas leak to a service breakdown, but the leak must not be left too long without attention.

If something is wrong with an important feeder, it must be taken out of commission for investigation, and then difficulties begin. In one case of gas leakage in a direct-laid cable, three months elapsed between taking out and putting back into commission. In a second case of bomb damage, the period was two months. We are accustomed to much more accurate and speedy handling of electrical faults than is at present possible with gas, and the manufacturers of the cable must concentrate on bringing the gas characteristics of the cable to the same high level as its electrical characteristics. Will the authors state the lowest temperature at which this cable can be safely handled?

Mr. R. H. Coates: Previous speakers have dealt with the practical points of this cable and, bearing in mind that they represent users of most of the 33-kV cable of this type laid in this country, and that their views are based on some years of experience, their comments carry considerable weight. I would, however, like to raise some technical points.

In 1935, two papers on the mechanism of the breakdown of cables were presented to The Institution by D. M. Robinson* and L. G. Brazier,† and the theories then propounded are, I believe, now generally accepted.

From the point of view of cable failure due to excess electrical stress, the authors go to great lengths to show how they have scientifically designed their cable to give very accurate control, and its "clean sheet" achieved to date is not surprising. We have, in fact, a cable that will not break down owing to electric failure—a comment which applies equally to oil-filled cables. This eases the previous feeling of caution in the users' minds in exceeding permissible loadings as published, which are undoubtedly conservative, and it is to be regretted that the authors give little information on the thermal instability of this cable and its permissible temperature of operation.

Section 10 notes that bad thermal conditions do not affect this cable detrimentally, which sounds too good to be true, or does it mean that the cable is normally much under-run?

Cables, speaking generally, are the one item of plant the supply industry uses without full-load temperature tests after installation. Having myself carried out several such tests on large cable circuits while in commission, and found very great variation in their thermal condition, I feel that any improvement in cable construction that enables us to consider operating temperatures, without any fear as to their effect on the electrical properties of the cable, is an important step forward.

Will the authors give further information as to the impulse strength of their cable, since E.R.A. Report L/T125 comments unfavourably on dry cables? In Section 3.3.1 figures are given of the maximum electrical stress of gas-filled cables. What are the corresponding figures for standard 33-kV and 11-kV solid cables, particularly belted types, as Fig. 3 would indicate that they are all operated above their ionization stress?

Finally, in Section 3.3.3 the thermal resistivity of the dielectric is given at 200 lb/in^2. What is it at 100 lb/in^2 and 14 lb/in^2?

* "The Breakdown Mechanism of Impregnated Paper Cables," *Journal I.E.E.*, 1935, 77, p. 90.
† "The Breakdown of Cables by Thermal Instability," *ibid.*, p. 104.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. C. J. Beaver and E. L. Davey (*in reply*): We shall deal first with those points which have been raised by more than one speaker.

Gas-Leak Location: In practice this has seldom to be faced, but we agree that the present method of locating a gas leak is slow and involves much labour. We hope that it will be possible, in

the near future, to put forward an improved method of location, not involving opening up the cable system. When a dome is removed while the cable is under full gas pressure, the pressure within the joint insulation is relieved by the gas path afforded by the pipe from the sheath to the dome. On double lead-sheathed cables if a leak occurs in the inner sheath while the second sheath is intact, the gas will eventually leak out at the terminal ends of the second sheath where blow-off valves would be provided. If the second sheath is not intact, gas is injected at each end of this sheath and the flow is measured at joints to locate the defect in it.

The method of gas-leak location put forward by Mr. Calvert (p. 368) indicates the position of very large leaks, but the main difficulty with the method is the determination of the point (E) on the graph. We have not done many tests with this method as we are developing other methods of leak location.

Cable under gas-leak conditions. Provided the gas pressure does not fall below 125 lb/in^2 (gauge) we consider that the cable will not be damaged by ionization. In general with a small leak, the gas pressure immediately under the sheath at the defect is appreciably higher than the atmospheric pressure. Nitrogen from a leak percolating into cellars, ducts or manholes would cause no trouble. Under leak conditions the pressure distribution in the cable, as shown in the paper, is independent of the absolute gas-flow resistance of the cable, providing it is uniformly distributed; it has not been necessary to use extra gas channels to ensure that the drop of pressure with a leak is communicated rapidly to the feeding points. These remarks apply only of course, to the pre-impregnated gas-filled cable.

Referring to Mr. MacQueen's remarks (p. 364), we agree that with a gas leak occurring when the cable is at the maximum temperature of 80° C, the pressure will fall to 180 lb/in^2 before the alarm operates. If the temperature is maintained, then the gas density at the conductor surface will fall to 81% of the value corresponding to a conductor temperature of 15° C. Converting this into a change of pressure so that a comparison can be made with Fig. 20(*b*), the equivalent gas pressure at the strand would be 100 lb/in^2 (gauge) at 15° C. Assuming a sheath temperature of approximately 50° C, the gas density here would be 90% of that at 15° C, equivalent to 13·5 lb/in^2 (absolute) at 15° C. Thus an equivalent pressure curve can be drawn in Fig. 20(*b*) starting from 100 lb/in^2 (gauge) at the strand and ending at 13·5 lb/in^2 (absolute) at the screen. It can be seen that a small extra portion of the dielectric ionizes close to the leak, but that would not be serious. Mr. Ledsom's suggestion (p. 368) regarding the checking of assumed sound sections of the cable after removal of a leaky length would offer advantages, if practicable.

Lead sheaths: The more important duty of the second sheath is to protect the reinforcing tapes against chemical corrosion. We prefer this method of protection to any other known to us. Cold working of the sheath occurs when it is distended beyond its elastic limit and then distorted back later during the working of the cable. Pure lead is generally used for the pressure-retaining sheath, while for the outer sheath that alloy is used which best suits the conditions. We agree that the integrity of the outer lead sheath is necessary to protect the metallic reinforcements, but this is a normal cable problem.

Surge strength: Under surges, when the gas-filled gaps are ionized, the electric stress is applied wholly to the impregnated-paper insulation, but the electric strength is ample from this aspect, especially in view of the surge-absorbing properties of the cable as mentioned in our reply to the London discussion. The flashover of the horns or rings on the sealing ends should occur before any other part of the cable system breaks down. A gas filling, instead of an oil filling, for the butt spaces gives a lower surge breakdown stress at atmospheric pressure, but the application of pressure brings the stress nearer to that of the oil-filled cable. Other means are also available for increasing the surge strength of the pre-impregnated paper part of the gas-filled dielectric.

Gas charging of the cable: About 1 to 2 days are required to charge up one mile of single-core gas-filled cable, when it is subjected to the full gas pressure for the first time after it has been installed. Routine gas-pressure tests are carried out in the factory at 30 lb/in^2 (gauge). Gas-pressure tests on sections of the cable during installation are desirable, provided they do not affect adversely any other part of the installation. It is permissible to allow a pressure difference of 50 lb/in^2 on a 220-yard length of 66-kV 3-core gas-filled cable during the charging, to show that there is no complete barrier to gas flow. When first charging an installation, the pressure should be raised in steps of 25 lb/in^2/hour; later it is permissible to recharge in steps of 100 lb/in^2/hour. Gas-feeding stations are recommended at distances of 2 to 3 miles to accelerate gas charging. After a repair has been completed the gas pressure is applied at the higher rate given above. The air is expelled from the cable while in the factory; this does not affect the length of cable which can be manufactured, for our stability tests indicate that the air is removed from the cable efficiently. In service, if a joint is dismantled, gas will be slowly emitted from the cable dielectric over a long period of time and this emission prevents the entry of air into the cable.

The fully-impregnated pressure cable: The disadvantages of using the so-called fully-impregnated dielectric for gas-pressure cables are higher permittivity and dielectric loss, while higher gas pressures will be generated during heating cycles. Gaps or butt spaces must be left between adjacent convolutions of paper lappings in this cable as in all cables, for the mechanical reasons explained in the paper.* These gaps in the fully-impregnated cable may be initially full of oil, but in service in vertically run sections this oil will drain when the cable is heated to 80° C, and the ionization stress of the drained portion will conform to the gas-filled-cable dielectric laws, i.e. it will depend upon the thickness of the gas film as controlled by the individual paper thickness and also on the gas pressure. A stability test on such a cable should test the cable in a vertical position with the upper portion isolated for dielectric power-factor tests, so that the electrical characteristics of a drained portion of the cable are obtained.† We do not think that under these conditions of test an ionization voltage of at least 4 times the working voltage will be obtained. Tests taken on the complete installation, i.e. the fully-impregnated part and the drained part, will give apparently higher ionization voltages since the sensitivity of the test set-up, as regards the detection of ionization, will be reduced or masked because the fully-impregnated portion is in parallel with the drained portion of cable.

A very great drawback arising from the use of the fully-impregnated dielectric for a gas-pressure cable is, in our opinion, that in the event of a gas leak the free oil would move within the cable sheath and would choke the joints and gas-feed channels and thus render gas-leak location very fortuitous.

Tests: We confirm that the dielectric power-factor/voltage tests can be carried out at the alarm pressure up to twice normal working voltage. The one-minute a.c. breakdown voltage of a gas-filled cable is approximately five times the working value. The breakdown of the gas-filled cable under high a.c. voltages is no more fortuitous than that of other cables. A normal design, such as we have manufactured in the past, will withstand four times the working voltage for 15 minutes; breakdown when it

* See also ROBINSON, D. M.: "Dielectric Phenomena in H.V. Cables," p. 30.
† *Ibid.*, p. 95.

occurs is found to be due to excessive heating caused by the ionization loss in the gas spaces. Clearly no such condition can occur in service with the continuous imposition of a working voltage well below the ionization value, and the occasional imposition of unidirectional surges up to several times the working voltage, but only of about 50 microseconds' duration.

Replies to Points of Individual Interest.

Prof. Marchant.—We are very glad to have the reference to the work of Mr. E. A. Watson in 1909 on the electric strength of compressed gases.

Mr. Bell.—We appreciate the importance of the design of joints and other accessories, and we realize that continuous attention should be paid to the development and improvement of these accessories.

Mr. Cave.—We have used the description "gas-filled" for our cable since all the space within the lead sheath not occupied by copper and impregnated paper is filled with gas, but we do not think that the term should be used for other types of cables, since these are really semi-oil-filled and semi-gas-filled. The adjustment of the ratio of compound to gas volume is not automatically effected by sheath distension if the initial ratio is incorrect, but causes an increase in the internal pressure at high temperatures; this is one of the drawbacks of the so-called fully-impregnated pressure cable.

Mr. Crocker.—The gas-filled cable is an economical proposition for 33 kV, but relative costs can only be given for specified conditions. Approximately 4 days are required to make a 132-kV joint. The cable will run satisfactorily for 24 hours with one phase of the system earthed. Joints made between papers on the lapping machine do not involve more than 2 paper thicknesses at any part of the joint.

Mr. Orchard.—We agree that 132-kV single cores can be used at the same stresses as 132-kV 3-core cables, and a comparison between them should be based on the same operating electrical stress. We use flexible conducting tape to ensure a perfect joint between the screen and the conducting material used to continue the screen across the joint. This tape is a graphitic-coated bias-cut silk tape with a breaking stretch of 30% and ensures that a perfect joint is made between the screen termination and the conducting material over the joint. We confirm that this tape is satisfactory for the screening of joints. The power-factor/voltage curve of a 132-kV joint alone would be flat up to 152-kV to earth; the corresponding value would be about 0·0070 at 15° C and 0·0100 at 80° C.

Mr. Macdonald.—The gas-filled cable does not behave any differently from other types of cable as regards dissipation of heat generated and the effects of various conditions of laying. The percentage of rejects of brass sleeves is very low, and although we have treated porous sleeves we have not found them to be satisfactory in operation.

Mr. Dunn.—The bending radius of the cable is exactly the same as for solid cables.

Mr. Richardson.—The drying temperature of the paper is about 250–300° C; drying takes about three seconds. The first 100 papers are applied in the same direction. The vacuum obtained in the impregnating machine is within about 0·5 in of absolute.

Mr. Lightle.—The speed of the paper through the drying and impregnating machine varies from 30 to 50 ft/minute.

Mr. Fletcher.—The total amount of compound inside the cable sheath is about 35–40% of the volume; thus the amount allowed on the drainage test is quite small and will not affect the operation of the cable in a vertical position. No gas known to the authors is superior to nitrogen for filling. Helium has a much lower ionization stress than nitrogen and hence would be uneconomical to use in a gas-filled cable.

Mr. Burgess.—The joint boxes are sealed by applying a thermoplastic compound seal on the pressure side of a cork or cork-rubber gasket. We have never used the thermoplastic compound alone. The arrangement described in the paper has been used on every joint and sealing end installed on our gas-filled cables.

Dr. Miller.—We agree that it may be an advantage to install gas-filled cables for low voltages in situations where compound migration is to be feared. The greatest objection to the development of the vacuum cable is that if the cable is damaged or punctured then, in normal situations, air and/or moisture would rapidly be sucked into the cable dielectric and the latter completely ruined. We agree that the replacement of impregnated paper with synthetic materials and also the introduction of gases superior to nitrogen may be expected within the next few years.

Dr. Meek.—We do not think that the breakdown gradient between insulating surfaces would increase as rapidly with pressure as the gradient between metal surfaces, since the breakdown in the former case might arise from fibres projecting from the surfaces of the papers; breakdown might also occur across the edge of the space, although the effects of fringing would reduce the stress in this region. Under d.c. conditions ionization does not occur in a void within a cable dielectric, since the leakage current through the solid dielectric is extremely low. If the d.c. voltage is raised rapidly enough, initial transient discharges occur in the void until the space charge formed in the void lowers the stress sufficiently to preclude ionization. We have not calculated the mechanical forces of attraction between opposite sides of the voids due to the presence of space charges, but it is possible that this might influence the bowing of the papers in the centre of the butt spaces, and hence cause the breakdown paths to be located away from the centre of these spaces, as described in the paper. The vacuum cable is referred to in our reply to Dr. Miller; other drawbacks are the difficulties of terminating the cable and of ensuring that the requisite degree of vacuum exists throughout.

Mr. Duncan.—Eventually the gas-filled cable will be a good economic proposition for use at 33 kV. Handling or bending has no effect on the dielectric of the cable. The approximate weight of 33-kV 3-core 0·3-in^2 cable is 45 lb/yd, and the maximum drum length 300 yards.

Mr. Szwander.—From the economic point of view, a pressure of 200 lb/in^2 is definitely necessary for gas-filled cables. The differences between the ionization stresses given in our Fig. 3 and those given by Shanklin is probably due to the differences in the permittivities of the dielectrics and in the maximum radial thicknesses of the gas spaces therein. Our data have been checked by independent authorities. The only difference between the cable and solid and oil-filled cable from the thermal time-constant aspect is that there is 20–25% of gas, instead of oil, space within the sheath.

Mr. Linley.—We agree that if the absolute pressure in gas spaces is below a certain very low value, then the dielectric strength of the space increases with further lowering of the pressure, but we do not think this condition obtains in a normal solid-type cable. The ionization stresses given in the paper were taken after installation in the laboratory and thus included the effects of bending, creasing and wrinkling of the papers. No evidence has been found of penetration of the joint compound into the cable via the taped crotches.

Mr. Shackleton.—In considering bending we have taken the maximum movement and stress occurring at the inside and outside of the bend, and dealt with the worst case for obvious reasons. We do not recommend S.L. gas-filled cables, except when they are convenient or absolutely necessary.

Mr. Partington.—The small quantity of air included in the joint insulation eventually diffuses through the cable system; the quantity involved is minute compared with the cable gas space. We consider that the gas-filled cable technique is applied to joints, except that in the 132-kV joint, compound is used as a dielectric in the outer portions. We find no drawback to the use, in laminations, of a mixture of sound dielectrics.

Mr. Buckingham.—The gas-pressure thrust in the sealing end is transferred via the upper metal ring, porcelain, and lower metal ring, to the base-plate and thence to the sealing-end structure.

Mr. Sayers.—Cable-system costs can only be given for specific cases and for definite material cost bases. We think it necessary to compound-fill joints in order to provide a second line of defence against gas leaks and a means for determining the direction of the gas flow at the joints in the case of a leak, so that it can be located.

Mr. Kibblewhite.—Ionization occurs in the gas-filled cable dielectric at about twice the working voltage; the service behaviour of systems which have been installed for some years indicates that this margin is ample to avoid deterioration at working voltage.

Mr. Kingsbury.—Venting of the space between the inner and outer porcelains is provided in the sealing ends both at the top and bottom. The use of Freon or similar gases will probably be investigated after the war.

Mr. Care.—The dielectric loss can be determined from the dielectric power-factor curve in Fig. 17, coupled with the knowledge that the permittivity of the dielectric is 2·8–3·0. The maximum conductor temperature is 80° C; we do not recommend any extra value to provide for overload rating.

Mr. MacQueen.—As stated in Section 5.1, no appreciable decrease of gas density occurs at the conductor surface at high temperatures. The presence of free compound in a gas cable is detrimental to the flow of gas. The joint compound is very viscous at the maximum temperature of operation, and our experience indicates that the silk-tape-lapped crotches form effective compound seals.

Mr. Ledsom.—We do not think that there is any risk of moisture being transferred from the jointers' hands to the jointing tapes. A joint filled solely with gas would suffer from the disadvantage of having a low surge strength, and there would be the risk of discharge occurring along the pencils, due to the vastly different permittivities of the gas and the cable insulation. The tape lappings also have the advantage of centralizing the conductor in the joint.

Mr. Mabbott.—The route described for the particular cable in Derbyshire is one for which the gas-filled cable is eminently suitable.

Mr. Nettleton.—In the American scheme the lead sheath is stripped from the cables as the latter are drawn into the pipes, which have previously been cleaned. No steps are taken to support the cores in the pipe against short-circuit stresses.

Mr. Haddock.—The cable can be handled safely at a temperature of 45° F.

Mr. Coates.—We have operated the gas-filled cable experimentally at conductor temperatures of 100° C, as compared with the rating of 80° C. The conductor-temperature rating is limited by the thermal-expansion effect which depends upon the average conductor temperature over the feeder length. The maximum electrical stresses for 33-kV and 11-kV solid cables are approximately 35–40 kV/cm and 25–35 kV/cm respectively. The thermal resistivity of the dielectric at 100 lb/in^2 is approximately 5%, and at 14 lb/in^2 10%, more than at 200 lb/in^2.

DISCUSSION ON "FLUORESCENT LAMPS"*

SHEFFIELD SUB-CENTRE, 17TH NOVEMBER, 1943

Mr. W. E. Burnand: I remember the Geissler tubes of 50 years ago, and how they glowed with a feeble excitation, having no apparent effect on a filament lamp, and the confident predictions that they represented the lamps of the future. Much later equally-confident statements were made that a solid was essential for efficient light production, but this seemed to be based on incomplete assumptions. The fluorescent lamp seems to be an intermediate and very useful step towards our goal of more light. As an apprentice, I rigged up about two dozen arc-lamps in a room about 10 by 15 ft. With all the lamps on, there was relief, not eyestrain, making manipulation of fine wires easy. Heat was the limiting factor.

In the fluorescent lamps, is the fluorescence of the powders used affected by their background, e.g. glass, metal, etc.? Would light production be more efficient if the powders could be kept in a state of suspension, the conditions then approaching those in the old flame arc-lamps? Also, how does the efficiency compare with that of the flame arc, and why does radio interference start only after the lamp has been burning a few minutes and increase for some minutes thereafter?

Mr. A. Haddock: I noticed that when the lamp with the partly-coated tube was lit, the light given by the inside of the fluorescent-powder coating was much brighter than that visible on the outside. This suggests that increased efficiency might be obtained if light could be radiated directly from an activated surface, as well as the use of ceiling panels coated with fluorescent powder and protected by sheets of quartz with ultra-violet sources of radiation arranged so that the radiation impinged on and activated the panels. The sources of ultra-violet radiation should, of course, be shielded from direct observation. The panels would then provide an extensive light source approximating very closely to natural sky lighting.

Mr. G. H. Fletcher: In large installations is it not possible to use high frequencies, e.g. of 500 c/s, as this would appear to have a number of advantages? First, the choke coil, which is fairly large and expensive in a 50-c/s fitting, would be reduced very considerably, or if a capacitor were used instead of a choke coil a frequency of perhaps even 1 000 or 2 000 c/s might be used which would reduce the capacitance required to a very small amount. The flicker so apparent with this type of lamp on low frequency would, I imagine, be completely eliminated at frequencies about 250 c/s or over.

I can conceive conditions which would make it very difficult

* Paper by L. J. DAVIES, H. R. RUFF and W. J. SCOTT (see 1942, 89, Part II, p. 447).

to use a tube 5 ft long, and I wonder whether it would be possible to bring it within a smaller compass, say by bending the tube and making it spiral.

Presumably, condensation of the mercury vapour takes place on the walls of the tubes, and I should like to ask whether part of this is absorbed by the coating, and, if so, whether such absorption has any deleterious effect on the coating.

Mr. H. Beattie: I am familiar with an installation in a department engaged in the repair and calibration of electricity meters, which demands a high degree of illumination. This installation comprises twenty-five 5ft fittings over an area of approximately 1 500 sq ft. Efficient lighting of the test benches provided a problem analogous to that of a piano, where good lighting on both the keys and the music is required.

Observations of this system have been made over the past two years. Early experiments proved the importance of keeping the fittings clean, and a mean level of 10 foot-candles over the working plane was achieved. Tube failures and light output per tube were carefully logged, and to date there have been 51 failures with an average life of 1 500 hours per tube. The performance in this respect is rather fickle because 23% gave less than 1 000 hours' life, 57% between 1 000 and 2 000, and the remaining 20% survived more than 2 000 hours. One tube was taken out of service after 3 700 hours on account of poor output. It would therefore seem that the authors' expressions "percentage normal life" and "twice that of a general-service incandescent lamp" are vague.

My results bear some resemblance to curve (*a*) in Fig. 22, which I believe is another form of a "normal" curve. I agree with the authors that curve (*c*) is typical of the diminishing light output met with in practice.

In Section 5.1.5 and Fig. 14 the authors show the relative ripple. Could the amplitude be expressed as a percentage, and if so, what degree of ripple would be considered injurious to the eyes? Have the medical profession conducted any experiments on fatigue of operators working under various forms of lighting?

It might be suggested that the ripple could be eliminated by staggering the units over three phases. This has been done and is only partially effective. I contend that the ripple is only nulled at a point equidistant from the three phases; at other points, the nulling effect is further weakened by the inverse-square-law phenomenon.

Mr. W. Fordham Cooper: To what extent is the stroboscopic effect and flicker dangerous as distinct from annoying with fluorescent tubes? It would seem that by adjusting the afterglow of the fluorescent materials, i.e. making them to some extent phosphorescent as well as fluorescent, this could be largely overcome. Is there any probability of this improvement being made in the near future?

Mr. R. H. Coates: The detailed description of the new fluorescent lamp given by the authors reveals that a major advance in the science of illumination has been realized almost unnoticed. For the first time, lighting engineers are able to provide a light of practically any wavelength or mixture of wavelengths and from a source of as low an intensity as desired. This means that the light can be adapted to the human eye and at once raises the question whether the medical profession knows sufficient about the eye to guide us in further developments.

Some of the difficulties are illustrated in the installation described by Mr. Beattie. For the type of work involved, one authority recommended 35 foot-candles, which seemed rather excessive, particularly as we found by experiment that the pupil of the eye contracts appreciably at 3 foot-candles, so that as the light is increased the eye will stop it down again. We decided on 10 foot-candles as a compromise, and with the standard fluorescent fittings this meant a height of 8 ft for the lamps, so that to remove the large unlighted area above the lamps, further ceiling fittings, using orthodox gas-filled lamps, were added, giving a further illumination at the working bench of 3 foot-candles.

Before deciding on the final arrangement, I read a detailed description of the construction of the human eye and its methods of functioning; I would recommend all lighting engineers to study this subject.

Have we a quantitative definition of dazzle? Apparently a very small source of high intensity can cause dazzle, even when it is in the same range of vision as other sources of much higher total-light emission which have a lower brightness.

Mr. E. G. Mackie: As a comprehensive treatment of the bearing of illumination on human vision is clearly impossible, I shall merely indicate some sources of information. In 1926, Lythgoe published a review, under the Medical Research Council, of literature on illumination and visual capacities. This is a publication of immense compression, but it is still an outstanding one for reference, and, with its bibliography, it gives detailed information on every aspect of the subject.

Another publication of interest is a Stationery Office Welfare Pamphlet "Lighting in Factories and Workshops," which gives the fundamentals of good lighting as: (1) adequacy; (2) suitability, (*a*) spread of illumination, (*b*) prevention of glare—from direct light in the worker's eyes, from reflection from his material, or by a distracting highly-contrasted light source inside his visual field in the working position, and (*c*) avoidance of shadows, which is closely related to (*a*).

Consideration of these desiderata indicates that they are all intimately related to illumination by point sources. In so far as fluorescent lighting provides *extensive* sources of lessened intensity, it appears to me to have met all the points in that publication, so that the paper may have to be re-written. It might be suggested that the fluorescent lamp represents a transition in lighting technique analogous to that which occurred in heating when it was realized that the "black panel," an extensive, low-intensity source, was more efficient than the small high-intensity source.

Mr. Coates has mentioned an experiment in which variations in lighting caused contraction of a subject's pupils. The pupil is not of inverse size to the intensity of incident light. The pupil contraction is the immediate protective mechanism. But real adaptation occurs in the retina by a rearrangement of the receptor elements (rods and cones) and the pigment epithelium, so that the latter surrounds and protects the receptors. When this retinal adaptation has occurred, the pupil enlarges again.

The optimum candle-power, or the threshold of harmful effects, have been asked for. From what I have said this is clearly most complex. Consider the high intensities successfully tolerated by man in natural surroundings, e.g. by our Middle East Forces, or in the Sudan. Harm, apart from point sources, is very unlikely. As regards working intensities, I feel that the quickest way to determine lighting needs is to measure industrial *output*. It is known that in artificial light, output is broadly 10% lower than by daylight. When the authors see that output with their lighting is 98% of daylight figures, they will be able to congratulate themselves on a highly successful performance.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. L. J. Davies, H. R. Ruff and W. J. Scott (*in reply*): Since the paper was read in Sheffield the discussions at Liverpool, Newcastle, Manchester and Birmingham have been published, together with our reply. Questions concerning the life of the

lamps by Mr. Beattie, on stroboscopic flicker by Mr. Fordham Cooper, and on high-frequency operation and curved lamps by Mr. Fletcher are covered in that reply.* As regards the life-test results given by Mr. Beattie, our experiences suggest that these possibly occurred on early lamps and that later observations should be much more encouraging.

Mention of the relative dispositions of powder and arc is made by Mr. Burnand and Mr. Haddock. Fortunately, ultra-violet radiation is transferred from all parts of the arc to the walls quite efficiently, so that fluorescent powder on the wall becomes adequately irradiated. While there is some loss of light due to absorption by the powder itself, which causes the inner surface to be brighter, the lamp output is also lower if one side of the arc tube is left bare; for a half-coated tube the decrease is approximately 25%. Greater losses are experienced if the fluorescent powder is put on external ceiling panels, since this entails further absorption of ultra-violet rays by the lamp envelope and by dust deposits on both lamp and panel.

* See 1943, 90, Part II, 478.

The efficiencies of some flame arc-lamps and the fluorescent lamp are similar.

Mr. Burnand and Mr. Wardale refer to radio interference caused by the lamps. The source is ionic and electronic radio frequency oscillations in the discharge itself; the frequencies and amplitudes of these oscillations are influenced by gas density and hence by temperature. Radio interference may be present when a lamp has just started, and may change in character as it warms up and also as the lamp ages. For normal domestic use a small suppressor unit can be supplied and is ample. For radio-laboratory work of extreme sensitivity, complete screening can be obtained by enclosing the fitting in an earthed wire-mesh cage.

The important relationship between light intensity and eye strain on working efficiency, raised by Mr. Burnand and Mr. Coates, has been largely answered by Mr. Mackie. There is no doubt that factory output records form one of the best checks on lighting efficacy, and that growing appreciation of this by engineers has accelerated the spread of fluorescent-lamp lighting.

DISCUSSION ON

"THE EFFECT OF THE NATIONAL GRID ON THE OPERATION AND MAINTENANCE OF SECONDARY POWER STATIONS"*

NORTH-EASTERN CENTRE, AT NEWCASTLE, 28TH FEBRUARY, 1944

Mr. J. B. Jackson: I cannot agree with the author's first conclusion in Section 5(*a*) that the natural process of reclassification of every station through its normal working life must continue and therefore it would be uneconomic to lay down plant or stations specifically to deal with peak loads only. On approaching the limit of efficiency obtainable with steam as the working fluid, it becomes harder and harder to make progress. Hence there is an increasing tendency for all new stations to have the same efficiency. There is also a tendency for the coal prices and wages to become uniform; hence a time is coming when the majority of stations will have an efficiency in the neighbourhood of, say, 26 per cent, and all will have roughly the same generating cost. Such differences as occur will be due to different coal-transport charges and different vacua according to the location of the station. The classification of a station will therefore be settled by its location and not by its age, and it is wrong to speak of a natural process of reclassification.

It is essential to remember this, because most of our stations are a compromise design to suit a base load in earlier life and a peak load in later life. The time is coming, or perhaps has come, when we must recognize that the station on a favourable site should always be in class A. Therefore, advanced features can be incorporated in its design, which would be inadmissible if that station had to undergo a process of declassification in later life. By this reasoning, I think we shall eventually design and build on favourable sites pure base-load stations having an efficiency of, say, 30 per cent, and then complete the picture by building simpler stations to carry peak loads only.

In Section 2.4 the author gives an expression which he applies to the vertical strips of a graded-load curve in order to estimate the performance of a secondary station. The expression contains seven unknowns. The vertical strip from the graded-load curve provides only two of these, hence the remaining unknowns must be estimated. Surely it can be inferred from this that the correct results are a compliment to the man who estimated the five unknowns, and not to the method which supplied the two unknowns. It would seem that this method could be tightened up very considerably by plotting, on the same basis as used for the graded-load curve, a graded standby curve and a curve of similar form showing boilers with fires in them. A vertical strip through these would supply information leading to a useful estimate of banking losses, turbine no-load losses, etc., and would permit a more complete calculation of the heat input to the station necessary to obtain the heat output represented by the area under the graded-load curve. We should thus obtain an annual efficiency under specific operating conditions. This method, it seems, would do something to overcome the difficulty in the author's conclusion that it is difficult to devise a factor of performance for secondary stations.

I suggest the points under discussion concern essentially the economy engineer and the expert estimator, and have no part in the daily routine of the power-station operating engineer who in a secondary station with frequent starting up and shutting down is a busy man, and does not spend much time in his office. For him it is probably better to institute a system of continuous plotting of certain selected pressures, temperatures and meter readings, from which he can quickly detect any change in running conditions. This would save time and possibly command more faith than involved calculations.

I agree that an interchange of indications between the boiler house and the switch house is good. It is very true, and not at all widely appreciated, that it is no use increasing load when the steam pressure is falling. I am not very clear, however, as to the

* Paper by R. A. W. CONNOR (see 1943, 90, Part II, p. 350).

purpose of frequency-time and standard-time clocks in the control room of a secondary power station.

The effect on maintenance of constant starting and shutting down has been widely covered in the paper. I have, however, heard of cases of alternator field-coil distortion due to this cause. What appears to happen is that the machine is run up to speed and the centrifugal force then clamps the copper bars against the slot wedges. Next, the excitation current is passed through the bars and heats them up but, being securely clamped, they are prevented from expanding longitudinally. The result is that the soft copper bars are stressed beyond their elastic limit and flow sideways in non-elastic expansion; in other words, the bars are deformed and finish with a larger cross-section. Later, when the machine is shut down and the centrifugal force removed, the deformed bars contract naturally and elastically, and we finish up with bars with a shortened length. Further, due to the different centrifugal forces and the different heating levels on the various turns in the slot this contraction is not regular and results in twisting of the cross-overs, which may produce faults between turns. Two cures have been adopted. One is to wind with hardened copper, which has a higher compressive strength and resists deformation. This has certain difficulties in manufacture, but appears to be effective. The other method is to block the end-turns with spacer pieces so that the cross-overs are forced to contract uniformly and shorting is avoided. This is the more common method in present use and is believed to be effective.

Mr. H. C. Ogden: The author draws the conclusion from Table 2 that there has been a levelling-up of thermal efficiency, from the bottom upwards. This has undoubtedly taken place, but a further result which would be expected from co-ordinated running would be an increase in the efficiency of the higher of the medium stations, and a reduction in the efficiency of the lower ones, thus reducing the number of stations in the medium-efficiency band. That this has actually occurred is borne out by Table 2; taking 15% to 19% as the range of medium-efficiency stations, the percentage of plant in this range fell from 53·3% in 1932 to 18·5% in 1938.

In discussing the subject of banking, the author refers to the alternative methods of normal banking and burning-off the fuel. It would be interesting if he could give some comparative data regarding the fuel consumed with these alternatives for various periods of non-steaming, allowing for the fact that with normal banking a certain amount of fuel generally attributed to banking is actually available for steam-raising when the boiler is again put on load. Can the author give any details of the differences in necessary maintenance and ease of putting back on load, using the two methods with refractory-lined furnaces and with water-cooled furnaces?

The boiler outage allowance of 3 to 8 days every six weeks for sooting and minor repairs, quoted in the paper, seems to be on the liberal side, since with a class B station 6 weeks represents only some 600 steaming hours.

The author mentions that, at low outputs, the works cost per unit varies very considerably with small changes in output, and there is therefore considerable difficulty in comparing stations which run under these conditions, particularly the class D and to some extent the class C stations. In these stations the fuel bill is small compared with the other works costs, while at these small outputs the latter can be considered to be fixed.

In deciding which stations shall be maintained available for use, the actual efficiency is not of such importance as the cost of keeping the plant serviceable. It seems therefore that the other works costs per kW could be used as the criterion in choosing which stations should be kept in use. Once this decision has been made, the loading of the chosen stations would be dictated by the incremental unit costs in the usual manner.

The relegation of stations from class A downwards in the course of time, mentioned by the author, has obtained up till now, as the efficiency of a new station has been normally very much higher than that of one built earlier. The rate of increase of efficiency is now slowing down and we are approaching an upper limit with existing methods and materials, with the result that the efficiency of new stations will be comparatively little better than that of their predecessors, so that the process of natural relegation will gradually cease. On the other hand, the delivered price of fuel still varies considerably from one district to another. These considerations show that the comparative fuel costs of stations will depend more and more on the delivered cost of fuel, and hence new stations in high fuel-cost districts may have to be designed for intermittent running from their inception.

Dr. J. C. Prescott: The paper shows most clearly the importance of boiler-house performance in the operation of a secondary power station. The boilers of such a station have to work under exacting conditions: not only must they be ready to supply comparatively sudden demands for increased output but they must operate with a reasonable efficiency when the peak load has been removed, and also must have small losses even when operating with banked fires during standby periods. I am glad that the author has insisted so strongly upon this point, for the flexibility of the steam supply to its turbines is the factor which affects fundamentally the capacity of a station to accept or relinquish loads quickly and efficiently.

In Section 2.4 some figures are given for percentage errors in the estimation of efficiency; it appears that in assessing the total error due to several causes the sum of the individual errors has been taken; if so this would give the maximum and not the probable error which last is, I assume, the one which is required. Again, in giving a figure for this error the author cites $\pm$ 4%, which looks formidable, but am I right in assuming that this is a percentage of a percentage and indicates that an efficiency given as 25% may be expected to lie between 26% and 24%?

Mr. R. W. Gregory: Regarding the author's first conclusion, I was interested a few years ago in a proposal to put down a water plant in the Galloway district, which was justified as being economical only as a peak-load plant. This water plant has thus blocked the natural process of the relegation of stations.

Mr. F. E. Heppenstall: Referring to the point raised by Mr. Gregory, Diesel-engine stations were installed for dealing with peak loads. Does the author suggest that these are no longer of any use?

Mr. B. H. Welch: I agree with the author that steam gauges ought to be supplied for the use of the switchgear attendant and load indicators for the boiler attendant, and that the working conditions of the boiler attendants should be made as congenial as possible by the introduction of centralized control.

Mr. Robinson: About 10 years ago I came across a station on the Continent which was hydraulically operated. At peak loads the water was allowed to run down from a lake on the top of the hill and drive the water turbine and generators. During low-load periods the water was pumped up into the lake again. Does the author agree with this practice?

Mr. E. C. I. Macdonald: Do the regular and extreme changes of load on the main transformers at secondary power stations resulting from the shift method of operation have any effect on the acidity of the oil or on sludge formation? Also do they accelerate the deterioration of the winding insulation?

On the question of efficiency, the trend of this discussion has suggested, I feel wrongly, that the selection of existing stations for relegation will become more and more difficult, because, owing to improvements in design, they will all be so efficient that there will be little or nothing to choose between old and new stations.

The implication follows that age as such does not matter. Surely it is quite wrong to ignore the inevitable effect of age on the overall efficiency of the plant and to assume that the relegation process is only the indirect effect of higher efficiencies in the newer plants due to better design? Would the author comment on the effect of age, and state how it is likely to affect relegation in comparison with the effect of better efficiencies in new plants?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. R. A. W. Connor (*in reply*): Many points raised have already been considered in my reply to the London discussion.

Mr. Jackson draws attention to the location of stations with regard to coal and circulating-water supplies and the important effect that these have on overall cost and, consequently, on classification. Although these are vital, the cost of transmission losses must also be considered. Owing to the increasing cost of coal and coal transport, the value of unit increment in thermal efficiency has increased, and this is most important in considering the siting of new stations. The delivered cost of coal to site may, however, become the deciding factor in station loading and classification in the future. The increasing value of efficiency makes routine methods of checking all sources of heat loss more necessary than ever.

The use of frequency-time and standard-time clocks in secondary power stations mentioned in Section 2.3 enables the staff to forecast imminent load-changes. It is found that, with modern ultra-sensitive frequency meters, the operating staff become very skilful in predicting routine instructions from the C.E.B. control, and economies can be made by such skilful anticipation.

Mr. Jackson's remarks on alternator field-coil distortion may account for some vibration troubles which have been incorrectly attributed to the steam end of turbo-alternators.

The subject of banking coal consumption raised by Mr. Ogden is a very difficult one. Extensive experiments made over a period of several months in one station proved that for the particular plant it was economic to keep fires banked with falling steam pressure for periods not exceeding 30 hours. It is necessary, however, to make complete tests with a particular plant before such rules can be made.

Dr. Prescott's assumptions with regard to percentage errors are quite correct. An efficiency given as 25% may be expected to lie between 26% and 24%, although as he points out, this is the maximum limit of error. The corresponding probable error can be calculated in the usual manner by the theory of errors and is about $\pm 2{\cdot}2\%$.

Messrs. Gregory, Heppenstall and Robinson are interested in the use of hydro-electric and Diesel-electric plant for peak loading purposes. Under certain conditions such plant may be an economic proposition; the deciding factor is, of course, the overall cost per kWh output. Even with the present high price of coal, I do not think that such plants could become economic in this country, except possibly in some of the smaller remote undertakings in Scotland. The same applies to hydro-electric pumped-water peak-load plants, although here it appears that capital charges on such plant might prove extremely high.

Mr. Macdonald inquires if regular and extreme changes of load accelerate acidity and sludge formation in transformers. My experience tends to show that this is so, but I do not think the effect is serious with modern transformers fitted with conservators.

The effect of age on plant depends largely on the standard of maintenance that has been followed throughout the life of the plant. If plant is neglected, deterioration in efficiency may be as much as 1½% per annum; that is, a plant running its first year with an efficiency of 25% may after 20 years' running give an efficiency of only 17·5% under identical conditions of loading. On the other hand, with regular and skilful maintenance the deterioration in efficiency is not likely to exceed one quarter to one half of 1 % per annum.

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A MODERN EARTH-FAULT RELAY EQUIPMENT FOR USE ON SYSTEMS PROTECTED BY PETERSEN COILS*

By L. B. S. GOLDS, Member,† and C. L. LIPMAN, Associate Member.‡

(*The paper was first received* 13*th July, and in revised form* 15*th December*, 1943. *It was read before a joint meeting of the* MEASUREMENTS *and* TRANSMISSION SECTIONS 18*th February*, 1944.)

SUMMARY

The paper deals with the automatic isolation or indication of earth faults on systems protected by Petersen coils. After discussing the principle of operation of this type of protection, describing the operation of a wattmeter-type relay, and enumerating the electrical constants of the system to which the protection is applied, the authors describe the application of the relay to a 66-kV distribution system.

The currents in the feeders are analysed and the problem of accurate current summation is discussed in detail. Laboratory tests are given on current transformers at small percentages of rated current approximating to the capacitance currents. A comparison is made between current summation by means of a summation transformer and by direct paralleling. Further test figures are given showing the effect of load current in addition to capacitance currents. The design of the relay element is described, emphasis being laid on its constructional features and operating characteristics.

(1) INTRODUCTION

The use of a relay of the directional type on unearthed systems was considered as long ago as 1930, but at that time Petersen coils had not been installed in this country, and hence little attention was paid to the theory of its operation or to its design. In a more recent paper§ dealing with the protection of lines by Petersen coils, mention was made of a wattmeter-type relay for indicating that an earth fault had occurred and assisting in its location. The voltage and current windings of the relay were energized respectively from a secondary winding on the Petersen coil and parallel-connected current transformers. Since the relay has not always given the reliability expected, the authors were led to look more carefully into its operation when designing a super-sensitive relay for use on a 66-kV system. They also hoped that a paper on the subject would be of service in adding generally to the knowledge of the operation of the Petersen coil circuit.

Where the apparatus on a system is capable of withstanding continuously the full line voltage to earth, only an indication of the faulty feeder is required. However, where the insulation of transformers or other apparatus is inadequate it is essential to isolate the faulty section automatically after a short specified period, while on the other hand retaining the advantage of the Petersen coil in its prevention of the restriking of arcs set up due to flashovers on insulators and other faults of a transient nature. In such cases greater reliability is required as the amount of line disconnected must be restricted to a minimum.

(2) LIST OF SYMBOLS

I_{C1}, I_{C2}, I_{C3} = earth-capacitance currents in phase conductors.
I_{CW} = active component of capacitance currents.
E_1, E_2, E_3 = phase-to-neutral voltages.
I_{CA}, I_{CB}, I_{CC}, etc. = Total earth-capacitance currents in feeders A, B, C, etc.
E_P = voltage across Petersen coil under fault conditions.
I_P = current in Petersen coil under fault conditions.
I_{PW} = active component of current in Petersen coil.
I_F = current in earth fault.
I_{FW} = active component of current in earth fault.
I_S = current-transformer residual current, energizing current coil of relay.
θ = phase displacement of I_{C1}, I_{C2}, I_{C3} relative to voltages producing them.
ϕ = phase displacement of I_S relative to E_P.
$\alpha = 90° - \theta$.
$I_C = \Sigma(I_{CA} + I_{CB} + \ldots)$.
I = minimum primary operating current of relay.
i = minimum secondary operating current of relay.
L_P = inductance of Petersen coil.
C_E = total capacitance to earth of the system.

(3) THEORETICAL CONSIDERATIONS

In order to obtain a clear conception of the operation of these relays, it is necessary to review briefly the fundamental Petersen coil circuit. In this discussion and in the subsequent description of the relay, the vector diagram will be employed extensively, as it is the phase relations as well as the magnitudes of the various currents and voltages which are of first importance. The vectors representing the insulation-loss currents of the overhead lines or cables and the active current of the coil are exaggerated, and the current-transformer secondary-current vectors are increased in the ratio of transformation.

* Measurements Section Paper.
† Edmundsons Electricity Corporation, Ltd.
‡ Nalder Bros. and Thompson, Ltd.
§ H. WILLOTT TAYLOR and P. F. STRITZL: "Line Protection by Petersen Coils, with Special Reference to Conditions prevailing in Great Britain," *Journal I.E.E.*, 1938, 82, p. 387.

Consider first a simple three-phase system without a Petersen coil in circuit, and with a fault between phase 3 and earth (Fig. 1*a*). Under these conditions there are two capacitances

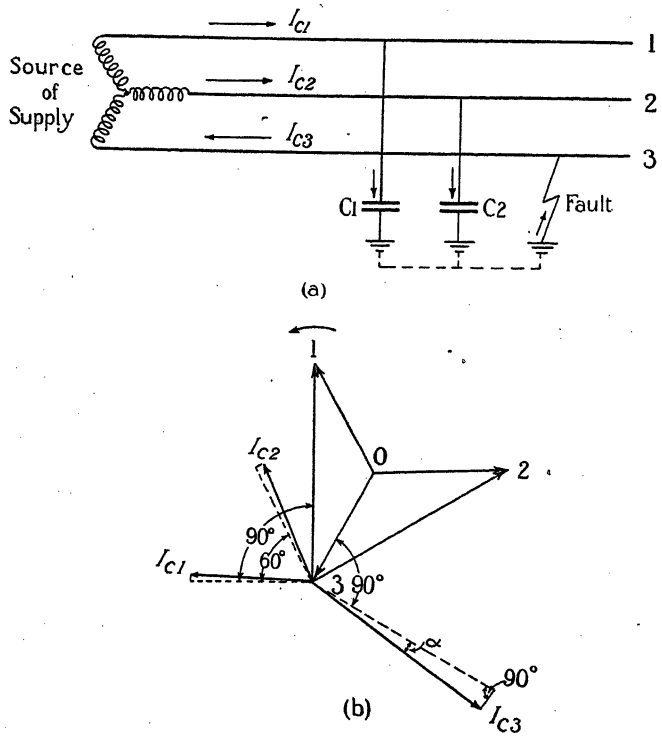


Fig. 1.—Three-phase system with unearthed neutral and with an earth fault on one phase.

(*a*) Schematic.
(*b*) Earth-fault currents.

C_1 and C_2 between the healthy phase conductors and earth. The potential of the neutral point is raised by phase-to-neutral volts above earth and that of the healthy phases to line volts above earth. Currents I_{C1} and I_{C2} will therefore flow in conductors 1 and 2, and their reversed vector sum I_{C3} will flow to the source via the fault and the faulty phase. Their phase relations, which should be particularly noted, are shown in Fig. 1*b*. The unsymmetrical currents I_{C1} and I_{C2} are shown leading the voltages producing them by an angle less than 90°, due to leakage over insulators and corona losses.

When a Petersen coil is connected between earth and the neutral of the system as in Fig. 2*a*, a voltage E_P, approximately equal to the phase-to-neutral voltage, appears across the coil. In other words, the fault completes a circuit from the source through the faulty phase, thence to earth via the fault, and so back to the coil and neutral. The coil causes a current to flow which lags behind the faulty phase-to-neutral voltage by an angle less than 90° owing to the losses of the coil. This current is therefore nearly 180° out of phase with the capacitance current I_{C3}, as shown in Fig. 2*b* where E_P and I_P have been superimposed on the unsymmetrical voltage and current system of Fig. 1*b*.

It will be seen that if the Petersen coil current I_P is made approximately equal to the capacitance current I_{C3} there will be only a small residual current in the fault and the faulty phase. When the reactive components of I_{C3} and I_P are exactly equal in magnitude, the fault current theoretically consists of the small components I_{CW} and I_{PW} which are in phase with E_P. The fact that these components are additive in the fault and faulty phase is of great importance. In practice I_{C3} and I_P are generally unequal but, providing the difference does not exceed a certain

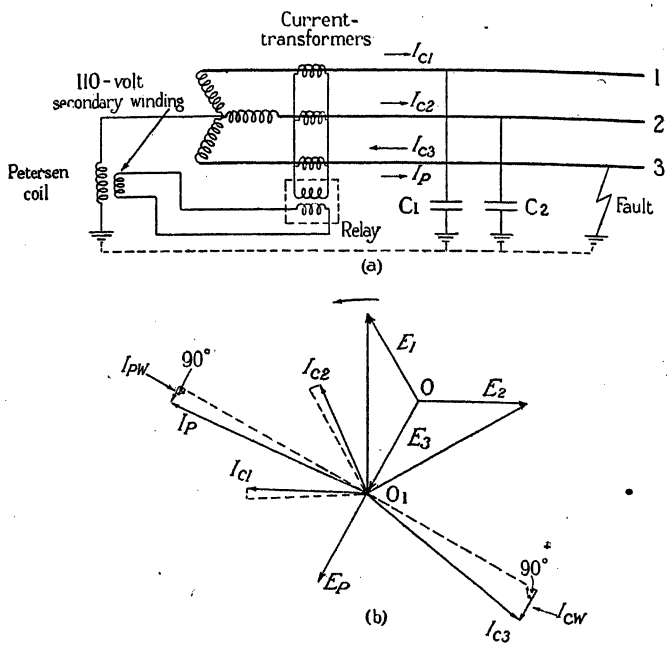


Fig. 2.—Three-phase system with Petersen-coil earthed neutral and with an earth fault on one phase.

(*a*) Schematic, including connections of an earth-fault relay.
(*b*) Currents under earth-fault conditions.

value depending upon the characteristics of the coil and the system voltage, the coil operates satisfactorily and not only quenches the arc but also prevents it from restriking. The amount by which I_P and I_{C3} differ is sometimes termed the "amount of out-of-tune," but this is rather misleading and it is suggested that "amount of under- or over-compensation" better describes the true state of affairs. Incidentally, under conditions of correct compensation $\omega L_P = 1/\omega C_E$, but actually there is no resonance at the time of an earth fault as the capacitance and inductance are supplied from different phases of the system.

Attention is drawn to the fact that the origin of the unsymmetrical voltage system (Fig. 2*b*) is at O_1. The vectors representing the voltages supplying power to this system must be drawn as acting away from this point, so that the voltage E_P across the Petersen coil is drawn in phase with E_3 and away from O_1.

Now examine the currents in the three current transformers connected in parallel in the usual manner. The current in the residual circuit is $I_{C1} + I_{C2} + I_{C3} + I_P = I_P$ (added vectorially). Therefore, if a wattmeter-type relay current coil is connected in this circuit with the voltage coil energized from a secondary-voltage winding on the Petersen coil, the power to operate the relay will be $I_{PW}E_P$.

It is obvious that system conditions and the characteristics of the coil affect the magnitude of the active component available to operate the relay. The characteristics of the coil are governed by the time that must be allowed for the system to regain its normal condition after the arc has been suppressed, and this in turn controls the power factor of the current to operate the relay under the worst condition when a relay is dealing with a single feeder, as in Fig. 2. A few typical examples will now be considered to illustrate its operation.

Consider first the system consisting of two parallel feeders fed from a common source of supply and protected by a Petersen coil, with a fault on phase 3 of feeder B (Fig. 3*a*). It is assumed that the lines A, B are the same length and have the same capacitance to earth. In feeder A there will be no earth-

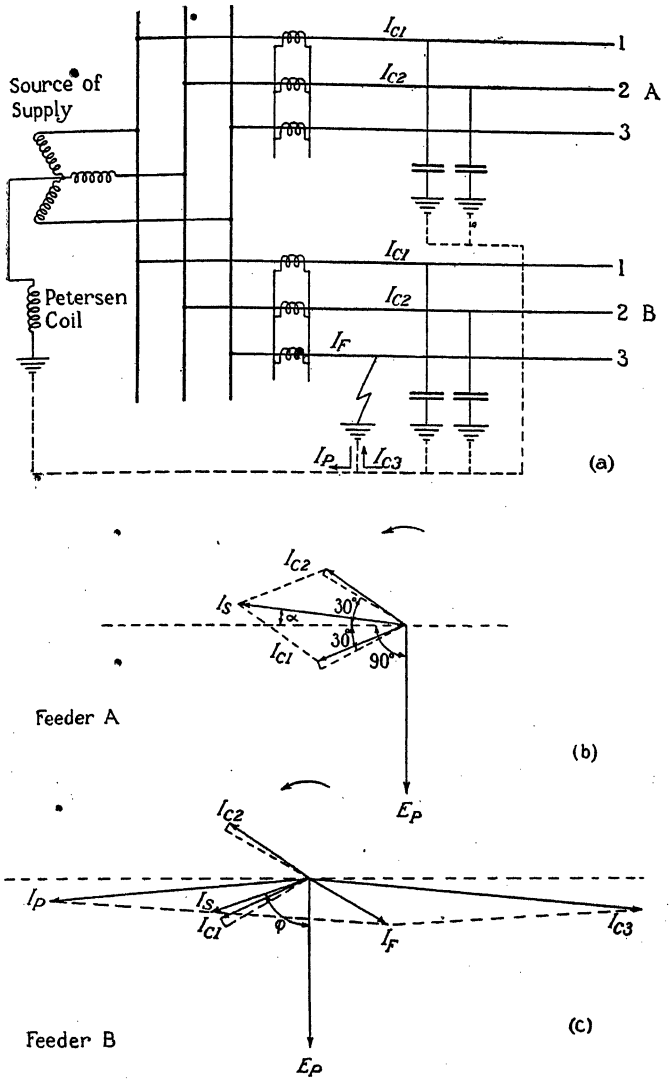


Fig. 3.—System consisting of two radial feeders.
(*a*) Schematic showing earth current I_{C3} and Petersen-coil current I_P.
(*b*) Earth-capacitance currents in Feeder A.
(*c*) Earth-capacitance currents in Feeder B.

capacitance current in phase 3, as this is at earth potential, but phases 1 and 2 will carry earth-capacitance currents I_{C1} and I_{C2}, the amount depending on the length and characteristics of the overhead line or cable. In the vector diagram (Fig. 3*b*), it will be seen that the resultant current I_S lags behind the voltage E_P by an angle $(90° + \alpha)$, where α is equal to $(90° - \theta)$, and cos θ is the power factor of the earth-capacitance current in the conductor. The relay in this feeder will therefore be restrained.

The line-to-earth charging currents I_{C1} and I_{C2} in feeder A return to the source through the fault on feeder B, together with similar currents of that feeder, making a total earth current I_{C3} which is approximately 180° out of phase with I_P, so that a resultant current I_F (the resultant of I_P and I_{C3}) appears in the fault and the faulty phase. The paralleled current transformers in feeder B therefore give a total current $I_S = I_{C1} + I_{C2} + I_{C3} + I_P$, where I_{C1} and I_{C2} are the charging currents in feeder B and I_{C3} is the reversed vector sum of I_{C1} and I_{C2} in feeders A and B. The current I_S lags or leads the voltage E_P by an angle ϕ which is less than 90°, so that the relay on this feeder will operate. The angle ϕ may be easily calculated from a knowledge of the active and reactive components of the current in the Petersen coil and the line-to-earth charging currents of the system and faulty feeder.

Under fault conditions, substations situated on radial feeders may be divided for simplicity into two types, those which have Petersen-coil current flowing in the busbars and those which carry earth-charging currents only. An example of each is given in the system shown in Fig. 4, the system consisting of two substations with a fault initially at X on feeder C.

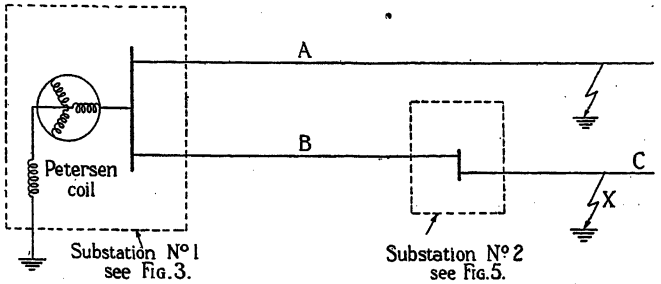


Fig. 4.—Example of system containing two types of substation.

The distribution of the currents at substation No. 1 has been discussed above and need not be considered further. Substation No. 2, shown in detail in Fig. 5, consists of the incoming

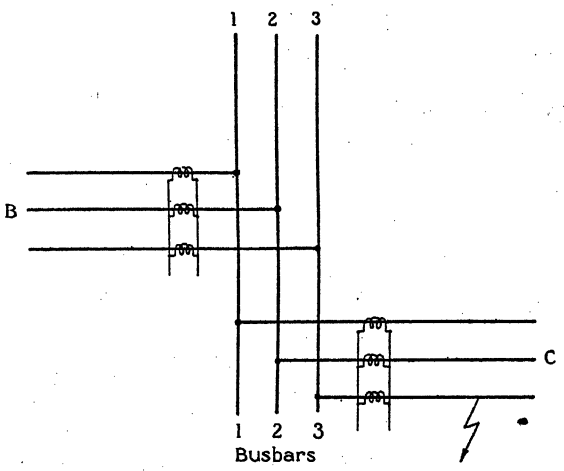


Fig. 5.—Busbars in substation No. 2 (see Fig. 4).

feeder B and an outgoing feeder C. Charging current is flowing in phases 1 and 2, and it returns in phase 3 as I_{C3}, but compensated by the Petersen-coil current. The vector diagram for the currents on the outgoing feeder towards the fault will be a repetition of Fig. 3*c*, except that currents I_{C1} and I_{C2} will be smaller in magnitude owing to the shorter length of feeder. The relay will operate similarly to that on feeder B at substation No. 1 and will therefore indicate a fault on feeder C.

The relay on feeder B at substation No. 2 will respond to the same residual current, but by reversing the connections from the current transformers to the current coil of the relay it will be restrained, thus indicating that the fault is not on feeder B.

The voltage for the relays may be derived at this substation from a five-limb broken-delta voltage transformer, or, if the substation is also used for feeding a local star-connected transformer, a neutral earthing transformer may be used. It will be seen that the connections are arranged so that the relays measure power being taken by the feeder in which they are connected.

Referring again to Fig. 4, let it now be assumed that the fault is transferred to feeder A. As a result substation No. 2 is feeding a healthy part of the system. The vector diagram for

feeder C will be the same as Fig. 3*b* and the relay will be restrained, but the secondary-current vectors for feeder B will be reversed owing to the reversal of the connections from the current transformers mentioned above, so that the relay will tend to operate. The sum of the capacitance currents of the two healthy phases I_S now leads the voltage E_P by $(90° - \alpha)$, the angle α, as shown previously, being dependent upon the leakage current and corona losses of the line, and the power available to operate the relay being $E_P I_{CW}$.

Summarizing the foregoing, in a substation where Petersen coil current is flowing in the busbars, the relay on a faulty feeder will trip, the relay on a healthy feeder will be restrained, and the relay on the Petersen-coil side of the busbars will also be restrained. In substations with no Petersen-coil current in the busbars, relays on the side of the busbars remote from the Petersen coil will be restrained while those on the incoming side will tend to trip.

The conditions that have been outlined above for radial feeders apply in the same manner to ring-main feeders. The fault current is, however, split up round the ring as also is the charging current I_C, although not necessarily in the same proportion. It is therefore possible that on some feeders the active component of the residual current may not be sufficient to operate the relay. This, however, only applies where the relay is used for indication. Where it is used for switch tripping the feeder switch carrying the fault current will trip, thus causing the ring to open and the fault current to be fed round the ring, whereupon the relays will operate as for a radial feeder.

An illustration of such a case is shown in Fig. 6, where a ring

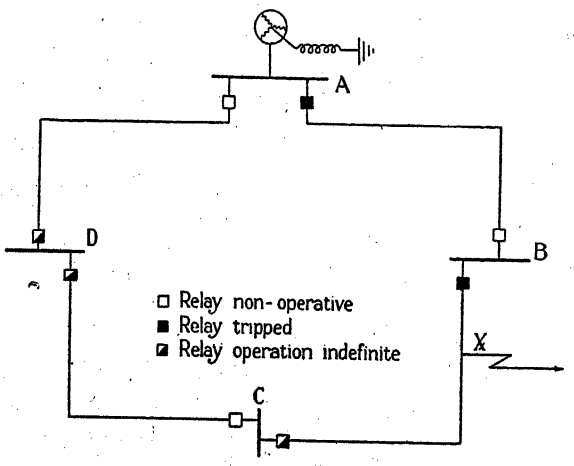


Fig. 6.—Ring-main feeder equipped with earth-fault relays for indication.

main is fed from a substation A equipped with a Petersen coil. If a fault occurs at a point X between substations B and C, such that about 90% of the Petersen-coil current flows via substation B, and the charging currents I_{C1} and I_{C2} are supplied equally through the two feeders AB and AD, then the arrangement of vectors for the unsymmetrical system on the feeder AD is as shown in Fig. 7. This is due to the fact that the line-to-earth capacitance currents I_C in the system all flow through the fault and take the lower-impedance path back to the source through the faulty phase. The result of this distribution of fault current is that relays at substations C and D will either show that that part of the system is healthy or will not indicate. In any case, the relays at substation A will indicate that the fault is nearer B as the relay on feeder AD will not operate until the ring is opened between the fault and the substation either at A or B.

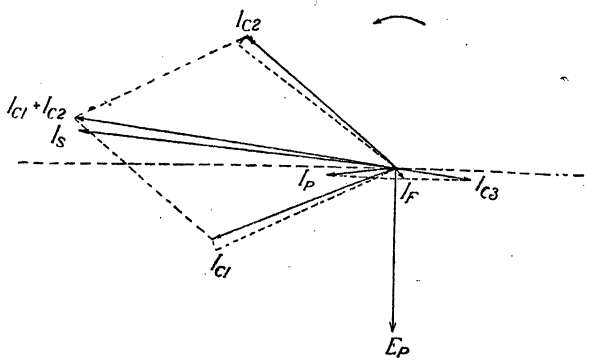


Fig. 7.—Capacitance currents in incoming feeder at substation D (Fig. 14).

(4) ANALYSIS OF THE CURRENTS IN HEALTHY AND FAULTY FEEDERS

Before dealing with the design of the relay it is proposed to digress at some length to describe the currents in the current-transformer primary windings on healthy and faulty feeders and the effect of the current transformers in transforming these currents.

In the vector diagrams which have been given to show the relation of the currents and voltages in the system and to show the principle of operation of the relay, the vectors of the earth-capacitance current system have been drawn with the earth as the origin. Vectorially these diagrams are correct, but electrically the earth currents are carried by the phase conductors. The resultant currents in the three-phase system comprise: (*a*) load currents; (*b*) interphase capacitance currents; (*c*) earth-capacitance currents; (*d*) Petersen coil current. The currents will vary in magnitude and phase depending upon load and weather conditions, but they can be analysed into positive, negative and zero sequence components. Currents (*a*) and (*b*) comprise the positive and negative components, and must sum to zero, whereas currents (*c*) and (*d*) sum to three times the zero sequence component, and form the residual current. It is obvious that the phase angle of this in relation to the faulty phase voltage is a vital factor in the proper operation of the relay.

The effect of imperfections in the current transformers on these components is:—

(1) To cause currents (*a*) and (*b*) not to sum to zero due to the differences in ratio and phase-angle errors of the current transformers, with the result that a voltage exists across the two points where the three transformers are paralleled.

(2) To cause the residual current to change in magnitude and phase angle owing to (1) and to the ratio and phase-angle errors of the current transformers at the current corresponding to the residual current.

The burden on the current transformers for the positive and negative sequence currents may be conceived as being that of the current transformers themselves and the connecting leads up to the point at which they are paralleled. In the event of the currents being balanced and the current-transformer errors identical, there would be zero voltage at the paralleling point. In practice this will not occur and there will be a small voltage which must be added vectorially to that of the zero sequence currents. The resultant voltage determines the magnetizing currents of the three transformers; this will be demonstrated more fully later, but it will now be shown how the currents will vary in magnitude in the healthy and faulty feeders.

On healthy feeders, the vector diagrams of which are given in Fig. 3*b*, it will be seen that earth-capacitance currents are flowing in the two healthy phases. For the sake of simplicity,

let it be assumed that the load and interphase capacitance currents produce an approximately balanced load at unity power factor to which must be added the capacitance currents to earth, so that the resultant phase currents under faulty system conditions will be as in Fig. 8*a*, which shows that the currents will be unbalanced and that transformation errors will occur.

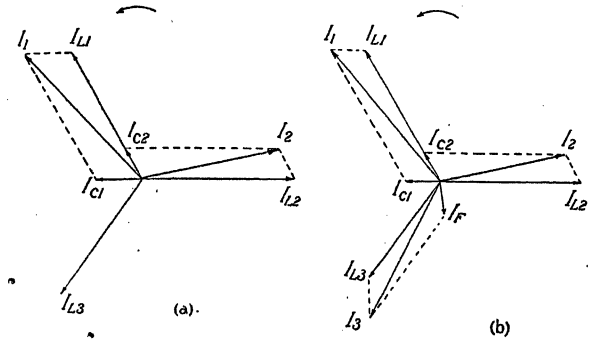


Fig. 8.—Combined load and capacitance currents.

Now let it be imagined that a fault occurs on the feeder which has just been considered. The earth-capacitance currents are unchanged, but the faulty phase carries the residual earth-fault current whose phase angle will change according to the amount of over- or under-compensation. This is shown in Fig. 8*b*. Here again unbalanced currents occur, but normally each current transformer is contributing to the residual currents in the relay. It can, however, be visualized that it is possible to have a condition where a fault occcurs on a short feeder when the only current is the residual fault current, which will be of the order of 2 or 3 amp. This may be a small percentage of the rated current and must provide magnetizing current for the current transformer on the healthy phases, while at the same time energizing the relay current coil.

The problem of designing a relay equipment which will discriminate under all conditions between the active component of the Petersen-coil current and the leakage losses of a healthy feeder resolves itself into two parts: (1) summing accurately all the currents in the three phases, and (2) constructing a sensitive low-impedance relay element.

(5) CURRENT SUMMATION

In Section 4 it was shown that the problem of designing the equipment consisted partly in summing accurately the currents in the three phases which vary widely in phase. It has been assumed that paralleling the transformers is the best method of achieving this, but it may not be out of place to consider other methods and compare their merits. The best-known methods are the employment of:

Multi-element relay
Multi-coil relay
Summation current transformer
Paralleled current transformers
Core-balance transformer

(5.1) Multi-Element Relay

The principal objection to this method is the weight of the movement. In addition, the burden on each individual current transformer due to the load current is considerable as the torque of the relay at rated current must be high. Owing to the higher burden, the current-transformer errors change more rapidly with change of current, and considerable errors occur when, as previously mentioned, the currents are unbalanced. There is, however, no interaction between the transformers, which is helpful when two transformers are idle.

(5.2) Multi-Coil Relay

It is known that when applied to meters and instruments this method has much to commend it. It overcomes the difficulty of weight, but there is still the burden of each winding to be considered; the winding must carry the full line current and at the same time have sufficient torque to cause the operation of the relay at 1% (or less) of the rated current. The effect on the unbalanced currents in the conductors is therefore no better than in method (5.1). It has also been found that with the best efforts at satisfactory twinning it is difficult to balance two elements at all loads, and it is therefore unlikely to be better with three elements. It largely overcomes the effect of the idle current transformers.

(5.3) Summation Transformer

Figures have been published* which may give the impression that a summation transformer is capable of totalizing two or more circuits without the effect of the idle current-transformers being apparent. If this is so, it is likely to improve the phase-angle errors of the residual current. The relay-element winding has moreover, only to carry this current, thus simplifying the construction of the relay. By making a high-grade summation transformer with evenly-disposed primary and secondary windings, the burden on the main current-transformers is kept to a minimum. This method has much to commend it, and it has been thoroughly investigated. Details of the investigation will be given in Section 10.

(5.4) Parallel-Connected Secondaries of Current Transformers

This method also has much in its favour, as the burden on the individual current transformers is a minimum and the relay element winding, as in the previous method, has only to carry the totalized current. The effect of the idle current transformer(s) is considerable and the larger the magnetizing current the more marked is this effect; therefore, low ampere-turn bar-primary current transformers must be avoided wherever possible, but the use of high-permeability cores or the adoption of a compound transformer of the Wellings and Mayo type very materially helps matters. This method gives a smaller error due to unbalance of currents, but a larger error on zero sequence currents.

(5.5) Core-Balance Transformer

This is a complete answer to the problem if multiturn-primary current transformers are impracticable. On 6·6-kV and 11-kV systems, this method is of considerable value as the transformer can be slipped over the cable or wound over the cable on site. On h.v. outdoor switchgear this is obviously out of the question.

(6) SYSTEM CHARACTERISTICS

In considering the design of the relay and the associated current and voltage transformers, the factors which must be taken into account are peculiar to Petersen-coil-protected systems. These factors will now be dealt with in detail, as they affect the minimum operating power, the overall permissible phase-angle error and type of current transformers.

(6.1) Petersen Coil

The Petersen coil characteristics are dependent upon the voltage and capacity of the system, and, although its design is outside the scope of this paper, the characteristics control to a great extent the operation of this protection, because the iron and copper losses determine the minimum power available to

* E. W. Hill and G. F. Shotter: "Current-Transformer Summation," *Journal I.E.E.*, 1931, 69, p. 381; also, B. Hague: "Instrument Transformers" (Pitman), pp. 151 and 152.

effect operation. This minimum power occurs when the coil is protecting a single feeder (see Fig. 2). The residual current in the relay is then simply the Petersen-coil current divided by the current-transformer ratio. The power factor of the current with respect to the voltage on the relay voltage coil will also be the same as the power factor of the Petersen coil. It will therefore be seen that the relay must operate on less power than the losses of the Petersen coil. A minimum factor of safety to ensure the firm closing of the contacts must be fixed. It is suggested that the minimum operating current i of the relay should be made not less than 80% of the minimum current available.

(6.2) Rated Current and Voltage of the System

The load current on the feeder determines the rated current of the current transformers. If the power available to operate the relay is P_c, the voltage-transformer ratio k_v the current-transformer ratio k_c, and the minimum power to operate the relay element P_i, then $P_i = P_d/k_v k_c$.

(6.3) Insulation

On healthy feeders the power factor of the insulation and corona losses determines the phase angle between the voltage and the sum of the earth capacitance currents. The power factor of the insulation is a variable quantity depending upon a number of factors which are also outside the scope of this paper, but which may be as low as 0·01 and as high as 0·1. As a result, the angle α may be between 34 and 344 min, and the power factor of the relay current between $-0{\cdot}01$ and $-0{\cdot}1$ lagging. It is therefore clear that if the leading phase-error introduced by the current transformers exceeds this value the relay may operate and thereby trip out a healthy feeder. It will be clear, however, that the angle may be exceeded by an amount depending upon the minimum operating power of the relay for a given plug setting.

This angle is given by the expression

$$\alpha + \text{arc sin}(I/I_C)$$

where I_C = sum of earth-capacitance currents in feeders.
I = minimum primary operating current of relay.
$\alpha = 90° - \text{arc cos } \theta$. ($\cos\theta$ = power factor of I_C).

This angle will determine the maximum permissible phase-angle error of the three current transformers as a combination, if no allowance is made for errors in the relay element and voltage transformers.

(6.4) Type of Switchgear

This is important in that it affects the type of current transformers that can be used, and it is of particular importance where the switchgear designers have not been able—generally for economic reasons—to allow sufficient space to fit multiturn-primary current transformers. Such factors determine the output of the current transformers and hence the impedance of the relay element.

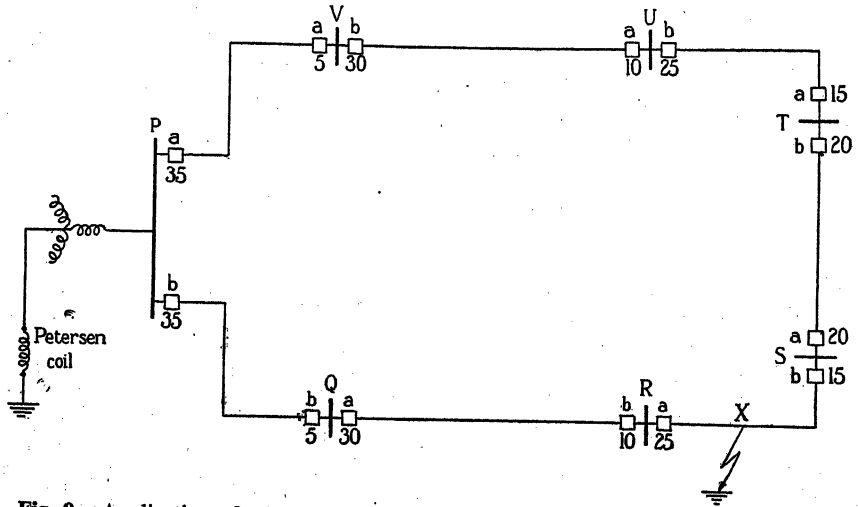


Fig. 9.—Application of relays and auxiliary timing relays to switch-tripping on a ring-main system.

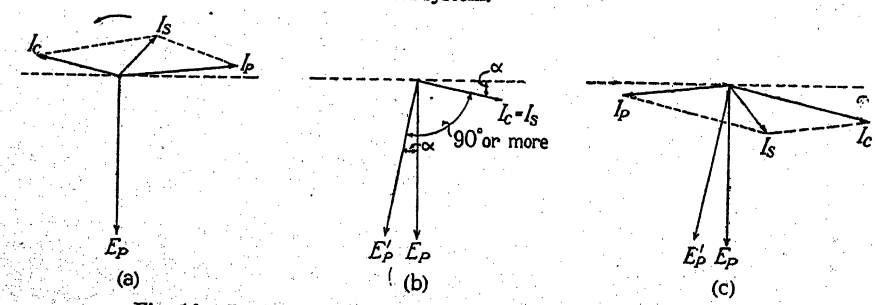


Fig. 10.—Residual currents in relay "b" at substation Q (Fig. 9).
(*a*) Before switch "a" at substation R opens.
(*b*) After switch "a" at substation R opens.
(*c*) For a fault between substations P and V, switch "b" at substation P first having operated.

I_G = net capacitance current in relay.
I_S = relay current.
E_P = Petersen-coil voltage.
E_P' = Lagging Petersen-coil voltage.

(7) APPLICATION TO SWITCH TRIPPING

When the relay is to be used for tripping a circuit breaker there are two further points to be considered:

(1) The available power to operate the relay increases with the distance of the substation from the source of supply. This power will vary with atmospheric conditions, so that it is not practicable to obtain reliable time-discrimination between relays under all conditions.

(2) There is a tendency for relays on incoming feeders of substations supplying healthy portions of the network to operate.

To obtain discrimination between switches on faulty feeders, it is therefore necessary to use auxiliary timing relays. The tendency to operate on healthy feeders is overcome by taking advantage of the fact that the phase of the charging current is fixed within certain limits, and making the relay inoperative under those conditions. The simple ring-main system shown in Fig. 9 illustrates this point. The relays are connected in the manner already described, but in addition they operate definite-time-delay relays which are given predetermined time settings and graded in the usual manner.

Now suppose for example that a fault occurs at point X and that there is insufficient fault current flowing through substations S, T, U, V to operate the relays at those stations. The relay at substation R, which is set for 25 sec, will, however, operate and thereby trip the switch "a" at that substation thus causing all the earth-fault current to flow through substations S, T, U, V, and leaving the portion of the system feeding substations Q and

R healthy. The incoming relay "b" at substation Q being on a healthy feeder, may operate and shut down the supply to substations Q and R. To avoid this the simple expedient is adopted of shifting the phase of the voltage of the relays on the *incoming* feeders of substations, so that there is insufficient power to cause the relays to operate under the worst condition of leakage. The method adopted to shift the phase is described in Section 9.

It is interesting to consider the vector diagrams for the relay on the incoming feeder "b" at substation Q under the following three conditions:—

Fig. 10(*a*). Before switch "a" at substation R opens.
Fig. 10(*b*). After switch "a" at substation R opens.
Fig. 10(*c*). If a fault occurs between substations P and Q, and switch "b" at substation P has opened. This last diagram is given to show that the artificial shift in phase of the voltage will not cause the relay to be inoperative on a faulty feeder.

It will be seen that the sum of the capacitance currents on the healthy system always leads the voltage by nearly the same angle, which is dependent upon the power factor of the leakage current, and further that the currents on the feeder under fault conditions are widely different in phase from the charging current. Therefore, by lagging the phase of the voltage flux, it is possible to make the relay on the incoming feeder inoperative for healthy charging current. The adjustment must not be carried to an excess; otherwise, under certain conditions of extreme under-compensation, there may not be sufficient active current to operate the relay under fault conditions. In the foregoing diagrams the earth-capacitance current of the whole system is shown as being under-compensated, but the phase of the current under these conditions differs materially from the healthy capacitance current.

(8) APPLICATION TO A 66-kV SYSTEM

Having discussed the protective scheme from a theoretical standpoint, the practical application to a particular distribution system, and the problems in connection therewith, will now be described. These problems largely concern the summation of the currents in the three phases of a feeder and are of considerable interest.

The system for which this protection was required (Fig. 11) consisted of about 120 miles of overhead transmission line of horizontal construction, compensated by two Petersen coils. The fact that certain apparatus would not withstand continuous operation at line voltage to earth, and the desirability of preventing a fallen conductor from being a source of danger, made it necessary to isolate a faulty section while leaving the rest of the system protected by the Petersen coil. The scheme described in Section 7 was therefore adopted. As pointed out in the Introduction, reliable operation of the relays is essential, otherwise stability, which is the chief advantage of the Petersen coil system, would be lost.

The technical data for the system will be dealt with in detail in the order adopted in Section 6, and its bearing on the design of the component parts of the equipment will be indicated.

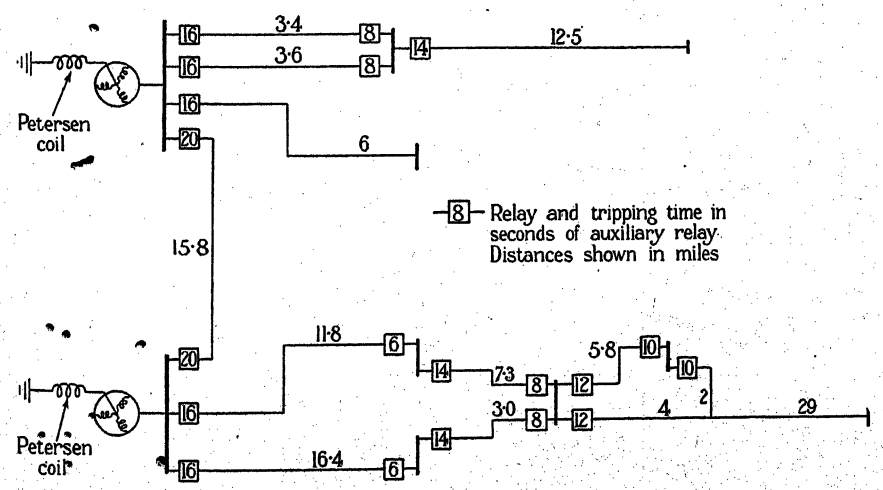


Fig. 11.—A 66-kV system equipped with Petersen coil and relays to isolate a faulty section in the event of a sustained earth fault.

(8.1) Determination of Minimum Fault Setting

(8.1.1) Petersen Coil

The total estimated earth-capacitance current of the system under fault conditions was 50 amp. To deal with this current and possible future extensions which materialized before the original scheme was commissioned, two Petersen coils with a capacity of 50 amp at 38 000 volts ($66\,000/\sqrt{3}$) were installed. The coils were tapped at the following percentages of their capacity: 100, 90, 80, 70, 60, 50, and the losses in kW at these tappings were estimated to be 36, 30, 24, 19·5, 15·5, 12. The minimum loss available to operate the relay equipment was therefore 12 kW at a power factor of 0·0126. As it is essential that the relay should operate with certainty, the equipment was made sufficiently sensitive to operate at 9·6 kW.

(8.1.2) Rated Voltage and Current of the System

As already mentioned, the voltage was 66 000 volts, and the maximum loadings on the feeders entailed the fitting of 300-amp current transformers; but there were certain feeders where existing 150-amp current transformers were installed. Due to the reduction to 1/25th of the burden of the leads it was decided to install 1-amp-secondary current transformers in preference to 5-amp.

The minimum secondary power for which the relay must operate is $(9{\cdot}6 \times 110)/(300 \times 38) = 0{\cdot}0925$ watt.

The minimum secondary operating current at 110 volts and unity power factor is 0·00084 amp, equivalent to 0·252 amp primary current.

(8.2) Determination of Permissible Phase-Angle Error

(8.2.1) Insulation

The power factor of 66-kV insulation has a minimum value of approximately 0·01, and it is important that the minimum figure be used when calculating the allowable phase error of the equipment. Any increase in leakage and corona losses due to atmospheric or other causes only tends to increase the value of α and hence the backward torque of the relay. The value of α for a power factor of 0·01 is 34 min, and with the data so far obtained a curve can be plotted from the expression given in Section 6 for the phase-angle error. In order to ensure stability, the value of i for the purpose of this calculation should be reduced by 50%, as an adequate allowance must be made for the various current-transformer errors. In the curve, which is given in Fig. 12, the 50% allowance has been made.

It is apparent from an inspection of the curve that the specification for the current transformers is not covered by any existing class in B.S. 81—1936, principally because figures are required for phase angle at less than 5% of the rated current. Therefore a special series of tests was made to obtain the data given in Sections 10 and 11.

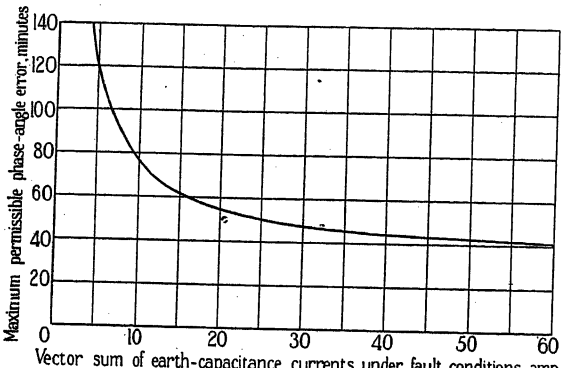


Fig. 12.—Relation between maximum phase-angle error and earth-capacitance currents for three parallel current transformers on a healthy feeder under fault conditions, with working burden and current in one transformer only.

(8.3) Type of Switchgear

The switchgear at the power station and at the majority of the substations was of the modern air-blast type, the current transformers being housed in bushings in the roofs of the switch houses. This limited the current transformers to 300 ampere-turns and caused one of the major problems in applying this protection to the system.

(9) DESIGN OF SUPER-SENSITIVE RELAY ELEMENT*

(9.1) Summary of Requirements

Before describing the design of the relay element, it is proposed to summarize the requirements that must be taken into account. Certain of these have already been discussed, and they are included here to make this summary complete and to emphasize that in designing the relay element consideration was given to the protective equipment as a whole.

The sensitivity of the relay must be such that it will operate definitely with the minimum secondary power, which is 0·0925 watt or 0·00084 amp at 110 volts and unity power factor, i.e. with less than 0·1% of the rated current. It is not necessary, however, for the relay to carry the rated current of 1 amp continuously, but it must be capable of carrying continuously the maximum capacitance current that is likely to occur on any system. It was estimated that this current would never be more than 50% of the rated current.

Owing to the possibility of earth faults occurring simultaneously on different feeders of the same system, the relay should be capable of withstanding the maximum secondary current for a short time, which in this instance is 2 sec. The maximum current would be determined by the characteristics of the current-transformers and the impedance of the relay.

The impedance of the relay must be as low as possible while retaining the above sensitivity, in order to reduce the phase-angle errors of the combination.

The relay must respond to the power component I_{SW} of the totalized system currents and it must close its contacts when the current, which is in phase with the Petersen-coil voltage E_P or its equivalent, produces a torque in the positive direction.

The relay must have a negligible change of phase-angle error with change of current for the range over which it has to work.

To facilitate adjustment on site for current- and voltage-transformer phase-angle errors and also to provide compensation for the angle α (in Fig. 10*b*) on the relay when situated on an incoming feeder, the relay should be fitted with an effective but simple means for adjusting the phase relationship between the working fluxes of the measuring element.

In order to make the relay stable under all system conditions, particularly on relays on the Petersen-coil side of the busbars of substations such as relay "a" at substation V in Fig. 9, it should be possible to decrease the sensitivity over a considerable range, the change of which should not unduly affect the phase-angle compensation to which reference has already been made.

The relay, although supersensitive, must also make positive contact free from bouncing. This is of particular importance as the relay is self-resetting and must operate a separate timing device.

(9.2) Working Parts and Principle

The measuring element of the relay, which was designed to meet the above requirements, comprises a fixed electromagnet and a moving system of the two-part rotor type, the magnetic and electric circuits of the relay being illustrated in Fig. 13 and the moving system in Fig. 14.

The laminated core of the electromagnet consists of three distinct parts: an external U-shaped main core, an internal core of cruciform shape, and an auxiliary core X magnetically in parallel with the main core.

The moving system consists of a main rotor D and an auxiliary rotor D_1, both made of aluminium and secured to the common spindle A. The spindle also carries the control spring S and the moving contact W. The main rotor is cylindrical in shape and is free to rotate in the air-gaps between the poles of the external and internal cores of the electromagnet.

The auxiliary core X is provided with an air-gap within which the auxiliary rotor D_1, in the form of a narrow flat strip, is free to move when the relay is in the operating condition.

The voltage winding VV on the yoke of the electromagnet produces a flux divided into two components, Φ_{EP} and Φ_a. The main component Φ_{EP} of the voltage flux, interacting with the flux Φ_{IS} due to the current coils M, L on the inner cruciform core, exerts a directional torque on the main rotor D, while Φ_a, the other component of the voltage flux (the auxiliary flux in the auxiliary core), tends to produce, by virtue of the shaded

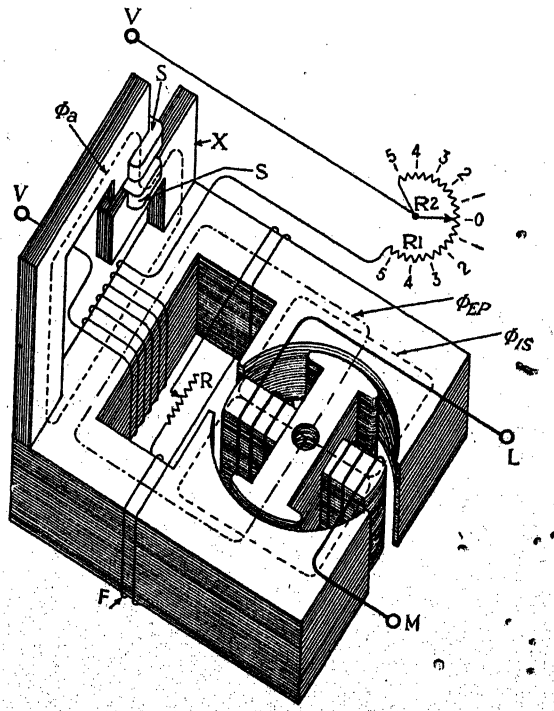


Fig. 13.—Principal electrical and magnetic circuits of relay.

* The relay is a development of the "Group A" relays previously described by C. L. Lipman in a paper on "Some Recent Advances in the Design of Relays for the Protection of Alternating Current Systems," *Journal I.E.E.*, 1931–32, 70, p. 545.

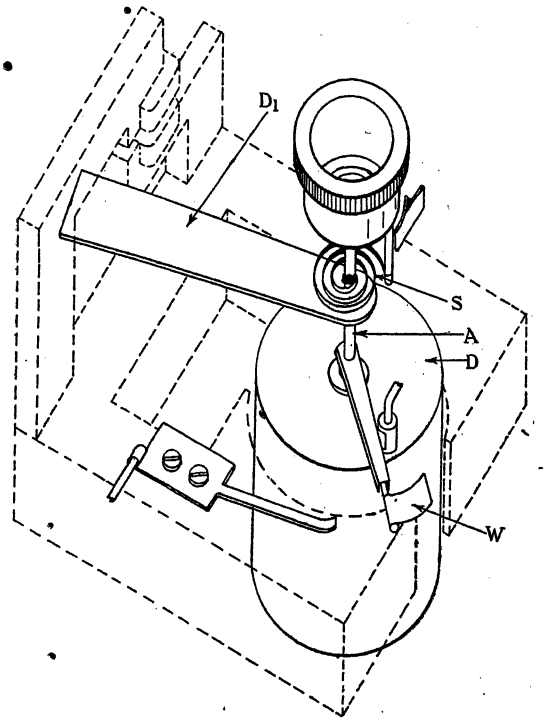


Fig. 14.—Moving system of relay.

poles SS, a unidirectional torque on the auxiliary rotor D_1 in the direction assisting the operating torque on the main rotor.

The flux-lagging coils F on the limbs of the U-core form a closed circuit of their own through a resistor R.

The voltage flux Φ_{EP} circulates along the path indicated by the chain line in Fig. 13, thus acting upon the cylinder D in a horizontal direction, whilst the current flux Φ_{IS} acts upon the same drum in a vertical direction, i.e. at 90 geometrical degrees from that of Φ_{EP}.

Resistor R is so adjusted that the fluxes Φ_{EP} and Φ_{IS} are also electrically displaced by 90 time-phase degrees when the current and voltage vectors are in phase with one another, i.e. at unity power factor on a single-phase circuit, when $\phi = 0$ as will be seen from the simplified vector diagram in Fig. 15.

These conditions being satisfied, a torque proportional to

$$I_S E_P \sin(90° - \phi) = I_S E_P \cos\phi$$

is exerted upon the main rotor D by the combined action of fluxes Φ_{EP} and Φ_{IS}, where I_S is the current flowing through the current coils and E_P the voltage applied to the voltage coil in series with a suitably chosen resistance R_1.

The relay is fitted with an adjustable rheostat R_1, R_2 in series with the voltage coil, whereby phase-angle compensation can readily be obtained in the following cases:—

(1) To compensate for the angle α (Fig. 10*b*) on the relay when situated on an incoming feeder.
(2) To compensate for voltage-transformer phase-angle errors.
(3) To compensate partially for current-transformer phase-angle errors.

The range of adjustment, which was considered to be sufficient in practice, is up to 5° "lead" and 5° "lag" from the mean "zero" position.

The current coil is designed to operate from current transformers with 1-amp secondaries and is provided with nominal current plug-settings of 1, 2, 3, 9 and 18 mA with the torsion head set in position 1. These values can be halved, doubled or trebled by adjusting the tension of the control spring by means of the calibrated knob.

An important feature of the current coil is its low impedance. Another feature is its high current-carrying capacity; when necessary, it is capable of carrying considerable overloads for short periods.

(9.3) Improved Contact Making

The growth of the "torque" with the "deflection," at minimum operating current, is illustrated in Fig. 16.

The straight line OD represents the torque in the operating direction exerted on rotor D by the watt-measuring element of the relay, and the curve OD_1 is the total torque tending to close the contacts of the relay. It will be noted that the additional torque DD_1 which the auxiliary electromagnet exerts on the auxiliary rotor D_1 is operative only at the end of the travel of the moving contact W (Fig. 14), thereby ensuring good contact-pressure without bouncing.

The relay is self-resetting and, although supersensitive, it works satisfactorily in conjunction with a separate timing device.

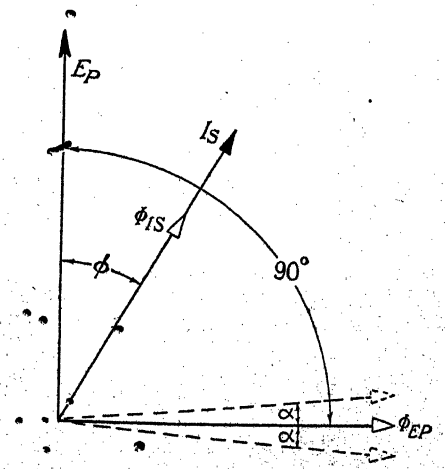


Fig. 15.—Relation between operating fluxes of relay watt-measuring element.

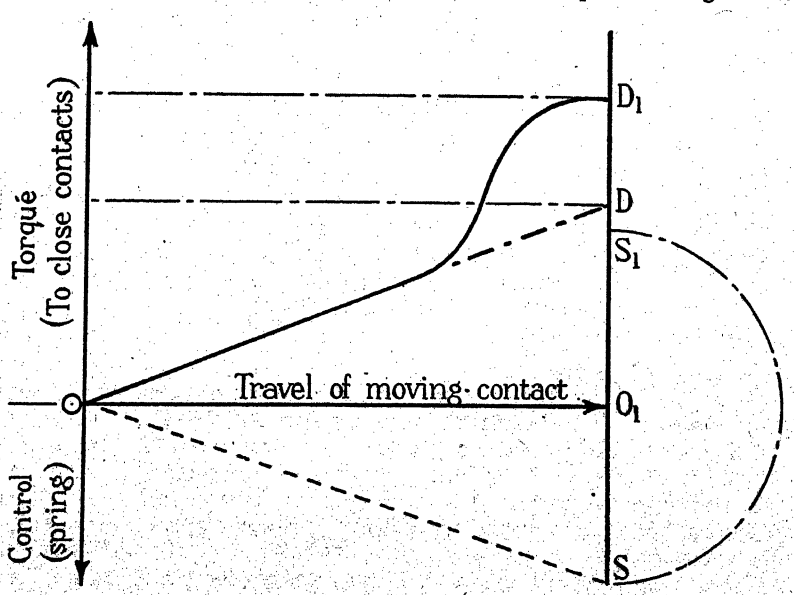


Fig. 16.—Torque/deflection curve of relay.

(10) SUMMATION OF CURRENTS IN A THREE-PHASE FEEDER

The purpose of the tests discussed below was to ascertain whether it was better to carry out the summation by three current transformers connected in parallel in the usual manner or connected to a summation current transformer as suggested in Section 5. Incidentally, this investigation is also of interest in the case of solidly-earthed systems where the effect of the paralleled transformers for earth-leakage protection accounts partly for the unsatisfactory operation of the protection on low fault-settings.

In Section 8.2 it was shown that the phase-angle errors of the equipment must not exceed those given in Fig. 12, which errors are given down to about 1% of full load. The greater part of the relay errors, made up of voltage-transformer phase-angle errors and the possible change of circuit constants of the relay current-coil at different plug settings, can be allowed for by the adjustment provided; therefore the errors of the current transformers as a group must not exceed those at any point on the curve. There was very little information available of the errors below 10% full load, so that the errors at this point were taken as a guide. The phase angle at this point is about 48 min for the three transformers; this was divided by 3, which gave 16 min as the approximate error at 10% load for each transformer. The performance of the transformers at loads in excess of full load is immaterial, but each transformer must have as flat a characteristic curve as possible up to full load. On this basis a set of three current transformers (A, B, C) was constructed to the specification given below.

BAR-PRIMARY CURRENT TRANSFORMER

Ratio	300/1
Secondary current	1 amp
Core dimensions:—	
Inside diameter	5¼ in
Outside diameter	7¼ in
Length	5 in
Material	0·015 Grade 3 Mumetal
Secondary resistance	3·4 ohms
Nominal rated burden	30 voltamperes
Secondary winding	300 turns, 0·032 in dia.
Test winding	150 turns, 0·040 in dia.

For the purposes of the test an experimental summation transformer was constructed to comply with class BL accuracy and the transformer was wound so that the errors on each winding were as nearly uniform as possible. The specification was as follows:—

TOROIDAL-RING SUMMATION TRANSFORMER

Nominal rated burden	30 voltamperes
Ratio	1 : 1 : 1/1
Secondary current	1 amp
Core dimensions:—	
Inside diameter	5½ in
Outside diameter	7½ in
Length	2 in
Material	0·015 Mumetal
Secondary and primary windings	900 turns
Resistance: each primary	4·9 ohms
secondary	2·7 ohms

To provide a standard for measurement, figures were obtained from the National Physical Laboratory on a class AL, 7·5-VA, multi-range standard current transformer, the figures on the 5/5 range being given in Table 1. These figures are extremely interesting as they show that the accuracy of precision current transformers does not change materially at low percentages of the rated current.

The test set developed by Mr. H. S. Petch was employed with a sensitive vibration galvanometer designed by Mr. D. C. Gall.

Table 1

N.P.L. TEST ON 5/5 RATIO OF STANDARD CURRENT TRANSFORMER

Percentage of rated current	Phase angle (min)	Percentage ratio error
120	+ 1·6	− 0·02
100	+ 1·7	− 0·02
60	+ 1·9	− 0·01
20	+ 2·3	− 0·01
10	+ 2·4	− 0·01
5	+ 2·5	− 0·01
2	+ 2·6	− 0·01
1	+ 2·6	− 0·01

A commencement was made by testing each current transformer separately and each primary to secondary of the summation transformer at its rated burden and at unity power factor (see Table 2, Tests 1 and 2).

Table 2

RATIO AND PHASE-ANGLE TESTS ON RING-TYPE CURRENT TRANSFORMERS AT RATED BURDEN AND UNITY POWER FACTOR

Test 1. *Tests on* 300/1, *Class BM*, 30-*VA Transformers A, B and C*

Percentage of rated current	A		B		C	
	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)
100	13·5+	0·45−	13·5+	0·48−	13·5+	0·54−
50	20·5+	0·45−	22·0+	0·48−	19·5+	0·55−
20	30·0+	0·38−	36·0+	0·41−	31·5+	0·52−
10	33·0+	0·35−	40·5+	0·38−	37·0+	0·47−
5	35·0+	0·31−	43·0+	0·35−	40·0+	0·45−
1	36·0+	0·35−	44·5+	0·34−	43·5+	0·43−

Test 2. *Tests on Winding* 1, 2 *and* 3 *of* 1/1 30-*VA Ring-Type Summation Current Transformer*

Percentage of rated current	Primary 1		Primary 2		Primary 3	
	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)
100	3·3+	0·10−	3·3+	0·10−	3·3+	0·10−
50	5·1+	0·09−	5·1+	0·09−	5·1+	0·09−
20	5·2+	0·12−	6·8+	0·07−	6·9+	0·07−
10	6·2+	0·12−	7·8+	0·06−	7·2+	0·06−
5	8·1+	0·07−	8·4+	0·06−	8·5+	0·06−
1	8·2+	0·07−	8·5+	0·06−	8·6+	0·06−

The errors at 10% load were considerably in excess of those given in the previous paragraph, but when the power factor of the burden was taken into account it was found that the phase errors were within the limits. The results are remarkable from the point of view of the small rate of increase of phase angle below 1/5th of full load, and the variation, although small, in the shape of the error curves of the summation transformer.

The three main transformers were now paralleled and a test made. Unfortunately the errors at 1% of full load were just outside the range of the set, but the increase in error can be gauged from the previous tests, the results being given in Table 3, Test 1. The effect of the paralleled current transformers is

Table 3

Test 1. Test on Paralleled Current Transformers A, B and C with Current in Transformer C

Percentage of rated current	Phase angle (min)	Ratio error (%)
100	37·0 +	1·39 −
50	58·0 +	1·42 −
20	82·5 +	1·31 −
10	94·0 +	1·24 −
5	101·0 +	1·20 −

Test 2. Test on Transformer C and Primary 3 of the Summation Transformer

Percentage of rated current	Phase angle (min)	Ratio error (%)
100	17·0 +	0·75 −
50	25·5 +	0·78 −
20	42·0 +	0·75 −
10	49·0 +	0·71 −
5	56·0 +	0·69 −

Test 3. Test on Transformer C with Transformers A and B connected to Summation Primaries 1 and 2

Percentage of rated current	Phase angle (min)	Ratio error (%)
100	41·5 +	1·70 −
50	64·5 +	1·77 −
20	97·0 +	1·70 −
10	100·0 +	1·60 −

approximately to multiply the errors by 3, although of course this depends on the power factor of the burden and the magnetizing currents of the transformers.

The transformers were disconnected and one transformer tested with one winding of the summation transformer. The errors are now approximately the sum of the two, although naturally the burden of the summation transformer will increase the errors of the main transformer. This is shown in Table 3, Test 2.

Finally, the two idle transformers were connected to the remaining primaries of the summation transformer,* the test results of which are given in Table 3, Test 3. If the effect of the summation transformer was to reduce the paralleling effect, it would result in the difference between Tests 2 and 3 being less than the difference between the errors of the single main transformer and the three paralleled. Clearly there is no reduction in the error nor are the overall errors less; they are in fact increased by the burden and the errors of the summation transformer. As shown in the earlier paper,† it is possible that these additional errors can be made small if the summation transformer is specially designed for metering with a low reactive internal burden.

The results confirm that the best method of summing feeders with current transformers with equal ratios and of measuring the residual current in a three-phase circuit is by means of paralleled transformers. At the same time it is necessary to emphasize that the ratio and phase-angle errors are considerably increased by the magnetizing currents of the idle transformers, and therefore it is necessary that the points brought out in the investigation should be borne in mind when designing the transformers.

(11) RATIO AND PHASE-ANGLE ERRORS OF TRANSFORMERS UNDER PHANTOM-LOAD CONDITIONS

These tests were made under three-phase conditions, first at rated burden and then using a relay as burden to ascertain whether the errors were within the limits under conditions likely to be encountered in practice. One set of conditions occurs when a three-phase balanced load is passing with the addition of the healthy phase-to-earth capacitance currents as indicated in Fig. 3*b*. A preliminary test was made to find whether the errors of the combined transformers with two currents 60° apart in two of three transformers gave the same errors as a single current $\sqrt{3}$ larger in one of the three current transformers. The test was made with a current of $30/\sqrt{3}$ amp in each transformer, the burden consisting of 30 ohms non-inductive resistance. The results are given in Table 4. The figures in brackets are taken from Table 3, Test 1, and are those with 30 amp in one transformer. These results confirm theoretical considerations which indicate that the figures should be the same.

Table 4

Percentage of rated current	Phase angle (min)	Ratio error (%)	Test conditions
$10/\sqrt{3}$.. ..	92·5 +	1·34 −	Current in two transformers
10	(94·0 +)	(1·24 −)	Current in one transformer (see Table 3, Test 1)

For all the subsequent tests use was made of a three-phase testing equipment and a separate single-phase equipment to supply the zero sequence current. The schematic diagram of connections is given in Fig. 17, where loading transformers are shown representing the two loading equipments. To check the phase relationships between the two systems, use was made of

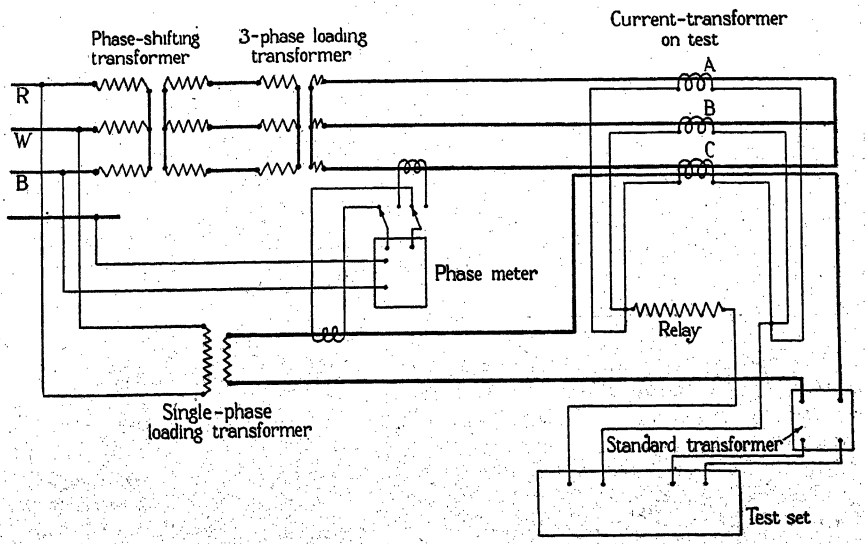


Fig. 17.—Schematic showing connections for Tests 1, 2, 3 and 4 of Table 5.

* See authors' reply to discussion, Fig. B(*b*), page 395.
† HILL and SHOTTER, *loc. cit.*

a single-phase phase-meter with its voltage coil energized from a common voltage circuit and its current coil supplied in turn from current transformers connected respectively in the three-phase and single-phase supplies. A phase-shifting transformer was interposed between the supply and the three-phase equipment so that any desired phase relation could be obtained between the two supplies.

The tests brought out a number of unexpected difficulties which were discovered because variable readings of phase-angle and ratio errors were obtained in check tests. They were due, broadly, to two causes: (1) contact resistance at the point where the three transformer leads were paralleled, and (2) interaction between the transformers.

The first trouble was easily overcome by soldering the three leads into lugs from which a lead was taken to the burden and the test set. The second was, however, more subtle as it was generally considered that toroidal-ring transformers were practically astatic; but, as previously mentioned, any small discrepancy between transformers will considerably affect the value of phase angle of the residual secondary current. This effect is shown in Tables 5 and 6 where the discrepancy between transformers caused by interaction results in considerable differences in the single-phase current as it becomes smaller in relation to the three-phase current. It was therefore decided that the final tests must be made with the same spacing between transformers as there would be when they were mounted on the switchgear.

Table 5

Tests showing the Effect of Interaction between Three Paralleled, Toroidally-Wound, 300/1, 30-*VA Current Transformers A, B, C, with a Burden of* 30 *ohms Non-Inductive Resistance. Transformers spaced* 51 *in between Centres*

Test	Three-phase amperes	Single-phase amperes	Phase angle (min)	Ratio error (%)	Test conditions
1	300	60	89·0+	1·41−	Three - phase current passed through primaries of transformers. Single - phase current (lagging 90° behind three-phase line current) passed through primary of transformer C in "blue" phase
	300	30	92·5+	1·40−	
	300	15	88·0+	1·46−	
	300	6	72·0+	1·66−	
	300	3	44·0+	2·01−	
2	300	60	87·0+	1·36−	As for Test 1, but transformer C changed to "white" phase and single - phase current lagging "white" phase by 90°. Transformer B changed to "blue" phase
	300	30	91·0+	1·29−	
	300	15	90·5+	1·24−	
	300	6	83·0+	1·04−	
	300	3	68·0+	0·66−	
3	300	60	88·0+	1·50−	As for Test 1, but single-phase current in phase with "blue" phase line current
	300	30	93·0+	1·55−	
	300	15	96·0+	1·69−	
	300	6	105·0+	2·15−	
4	300	60	78·0+	1·45−	As for Test 2, but single - phase current in phase with "white" phase line current
	300	30	81·0+	1·49−	
	300	15	81·5+	1·60−	
	300	6	80·0+	2·02−	

The tests given in Table 5 were made at 30-VA burden with the transformers connected to the three-phase equipment, the distance between centres was 51 in, and the transformers were disposed side by side. The transformers were interchanged in physical position (in order to find the actual amount of interaction), the single-phase leads also being transferred and the same phase displacement between line and single-phase currents maintained as before. A very marked difference is shown.

The tests given in Table 6 were made with burdens of the wattmeter-type relay, and from a comparison of the figures at the two burdens it will be seen that the phase angles of the three transformers lie within the curve given in Fig. 12.

Table 6

Test on Three Paralleled, Toroidally-Wound, 300/1, 30-*VA Current Transformers A, B, C, with Burden of Wattmeter-Type Relay described in Section* 9

Test	Three-phase amperes	Single-phase amperes	Phase angle (min)	Ratio error (%)	Test conditions
1	300	60	24·0+	2·37−	As for Table 5, Test 2
	300	30	24·5+	2·37−	
	300	15	24·5+	2·32−	
	300	6	16·5+	2·10−	
	300	3	4·0+	1·71−	
2	300	60	26·0+	2·55−	As for Table 5, Test 3
3	300	60	23·5+	2·45−	As for Table 5, Test 4

(12) CONCLUSION

From experience gained in practice in the operation of the relays both on tests with artificial faults and under actual earth-fault conditions, the relays were found to be perfectly reliable, providing that the equipment was connected correctly and that the current transformers were sufficiently accurate. In this respect Mumetal-core current transformers have been of great assistance.

When commissioning the gear an artificial fault is valuable in proving the reliability of the equipment. By observing the operation of the relays at each substation with faults at selected points the complete scheme can be put into operation with a minimum of testing. Preliminary tests are carried out by single- and three-phase injection to ensure that the transformers are balanced and that they comply with the specification.

It is not suggested that finality in the design of this form of protection has been reached, but with the increasing use of Petersen coils this form of selective tripping of faulty lines under certain circumstances may be of service. These relays are already being used in conjunction with phase-fault relays to switch-out one faulty line in the event of a double earth fault, leaving the original fault on the system. The difficulty of extreme sensitivity has been overcome by the use of a resistance in series with the coil which serves the double purpose of limiting the asymmetric current under healthy conditions and increasing the active component under fault conditions. This has the advantage of making the relay more robust, although the basic principles outlined still apply to its operation.

The authors would like to extend their acknowledgments and appreciation to Messrs. Edmundsons Electricity Corporation Ltd. and Messrs. Nalder Bros. and Thompson, Ltd., for permission to use the data contained in this paper; and to the Wessex Electricity Co., the South Wales Electric Power Co. and the Cornwall Electric Power Co., for their co-operation and assistance in carrying out tests.

DISCUSSION BEFORE A JOINT MEETING OF THE MEASUREMENTS AND TRANSMISSION SECTIONS, 18TH FEBRUARY, 1944

Mr. W. E. Milton Ayres: This paper is the result of painstaking investigation and close co-operation in elucidating the problems of this protective system. It is no easy matter tracking down a few minutes of phase angle on a commercial system. The justification, however, lies in the results, for it is now possible to install reliable discriminating protection with arc-suppression coils which will trip out a faulty section. The engineer's choice is no longer whether to leave the fault on or to short-circuit the coil, but whether to indicate the fault direction or trip the faulty feeder. In the main, radial systems will employ indicating relays, and duplicate supplies will favour tripping.

Some five years ago I installed indicating relays with arc-suppression coils over 750 square miles of rural area. Fortunately the combined coil currents were about 50 amp, and most of the current transformers were of the multi-turn type of only about 30 amp. Due to these favourable circumstances the phase angle did not get out of hand, and faulty indication was non-existent or very rare.

In Section 1 the authors state: "Where the insulation of transformers and other apparatus is inadequate it is essential to isolate the faulty section. . . ." I would like to suggest that the primary consideration is continuity of supply and that transformers and transmission lines should, and can easily, have adequate insulation. The class of apparatus which is most difficult to insulate for continuous full line pressure to earth is the slot-wound machine, such as the turbo-alternator.

In Section 3, I agree that under- and over-compensation is the more desirable expression and that there is no resonance at the time of an earth fault. This is not because the capacitance and inductance are drawn from different phases, but because the wattless components are tied to a definite voltage. An induction motor completely compensated to unity power factor by condensers has no resonance so long as it is connected to line voltage, although there is no question of different phases. In the same Section it is stated that the characteristics of the coil are governed by the time that must be allowed for the system to regain its normal condition. This is very much putting the cart before the horse. Arc extinction depends on the rate of rise of recovery voltage which is a minimum with lowest "total" losses for coil and dielectrics. These lowest losses, however, exaggerate the relay problem.

In Section 8.1 the power factor of the coil is given as 0·0063, but the coil capacity for 12-kW losses is 25 amp times 38 000 volts = 950 kVA; one would therefore expect a power factor of 0·0126.

We hear of better overhead-line insulator performance with a recently developed semi-conducting glaze which allows a leakage of some 50 milliamp per mile on 66-kV strings. I should like the authors' comments on the effect this may have on relay discrimination as outlined in the paper.

Mr. F. J. Lane: The authors are to be congratulated on the very painstaking way in which they have tackled the problem of applying discriminative protection to a system using Petersen-coil earthing. Examination in great detail is essential because of the very small margin in which correct operation can be obtained, and the necessity for such detailed consideration must produce an unfavourable reaction against any general application of the method.

In its consideration of the need for automatic protection on a Petersen-coil earthed system, however, the paper does represent a modification of the more usual dogmatic attitude that such a system requires no further earth-fault protection as one phase can remain earthed indefinitely. Sustained earth faults are a menace to continuity of supply and may involve public danger, and experience with Petersen coils shows that an appreciable proportion of coil operations are not successful in suppressing and clearing the fault. Records for 194 miles of 33-kV line during the first 9 months of 1943 show that out of 45 coil operations, 17 lasted for more than 5 seconds and were cleared by other protection.

It would seem to be a far better general practice to earth the system neutral point automatically through a resistance (or direct) if the fault is not suppressed within say 5 seconds—thereby permitting normal protective gear, with adequate operating margins, to clear the faulty circuit—than to attempt to use the coil currents as a basis for discriminative clearance, with the associated laborious preliminary investigation and limited relay operating margin of safety.

The application of a Petersen coil to a transmission system is usually accompanied by effects in addition to those mentioned in the paper. For example, the coil current contains an appreciable fifth harmonic component which must affect the relay operation. Also it is not usual for a coil to be precisely tuned to the system capacitance, so that both under- and over-tuning need to be taken into account. The capacitances of the three phases to ground are never accurately balanced, so that an unbalanced component of the charging current sets up partial resonance with the coil, limited by the coil losses, such that a noticeable voltage appears across the coil in normal conditions. Current-transformer characteristics are considered in detail in the paper, but there is little, if any, reference to voltage-transformer accuracy, which would seem to need equally careful investigation, particularly where, as suggested in Section 3, a five-limb broken-delta voltage transformer is used. I should welcome further comments on these additional factors.

Mr. H. Leyburn: What interests me most is the field of application of the relay described by the authors. As Mr. Lane has pointed out, the method usually adopted in Great Britain is to short-circuit the arc-suppression coil automatically, say 5 to 10 seconds after the occurrence of an earth fault, i.e. when sufficient time has elapsed to indicate that the fault is permanent. This makes it possible to use discriminating phase-fault protective equipment, which is usually installed on a system of any importance, to give also discriminative earth-fault protection at only slight additional cost and without current transformers of extreme accuracy, such as have to be used with the earth-fault relay described by the authors. On this account, as well as for the reasons mentioned below, the new relay is not likely to be used on such systems.

It is, however, particularly applicable to systems in which, as on the Continent, an earth fault is "held" or "sustained" until it can be disconnected by hand. The principal economic disadvantage of this method is that such systems have to be insulated to a higher level, say 20 to 30 per cent higher, than those in which earth faults are cut off quickly; and if relays of the type described by the authors are used their first cost, and particularly that of their associated special current transformers, has also to be taken into consideration.

A technical difficulty, which the authors refer to, but have not dealt with adequately, is to ensure that the relay on a healthy feeder pointing away from the fault shall operate satisfactorily. For this purpose they suggest the "simple" expedient of shifting the phase of the voltage of the relays on the incoming feeders of substations. This may appear simple at first sight, but even with the layout shown in Fig. 9 it is almost impossible to decide which of the feeders are incoming and which are outgoing; for

example feeders (*a*) and (*b*) at substations S and T. Is this determined by the direction of the normal-load current or by that of the capacitance current under earth-fault conditions? If the latter, the addition of a feeder to a system may alter the capacitance distribution and convert what has been an incoming feeder into an outgoing feeder, and vice versa. This difficulty is of course greatly accentuated, and may indeed become insurmountable, in a system more closely interconnected than that of Fig. 9.

These considerations lead me to the conclusion that the main field of application of the relay is to relatively unimportant and simple networks in which earth faults are sustained for some time, and not to systems, such as are more usual in Great Britain, in which they are automatically disconnected by discriminative protective gear, most of which has in any case to be provided for protection against phase faults.

Mr. D. E. Bird: I think the paper is particularly appropriate at this time in view of the almost certain big increase in the near future in the use of arc-suppression coils. May I suggest that they be called arc-suppression coils and not Petersen coils?

I do not think that the use of the continuously-rated coil or the coil which is to be used for sustained earth faults is quite so simple as the authors explain. On this point I do not altogether agree with earlier speakers. Systems with graded insulation, such as transformers or alternators with concentric windings, must have some device for short-circuiting the coil or otherwise cutting out the earth fault.

I am glad that Mr. Ayres does not think the insulation need be increased for the purpose of sustaining an earth fault. I agree, particularly with regard to 11- and 33-kV systems, many of which work very satisfactorily with the sustained earth-fault arrangement with normal insulation.

In a rural radial system, probably at 11-kV or possibly at 33-kV, a duplicate supply is not generally provided. If the feeder is tripped, several towns and villages may be deprived of their supply, when it is far better to sustain the fault. The chance of a double earth fault must be risked, but in practice the risk is not very great. On the other hand, on a 66-kV system supplying very large amounts of power, most power consumers have a duplicate system of mains. Therefore a section of the system can be cut out without interrupting the supply; this, I think, is the course which should be taken. On the latter type of system it must be decided whether to use a relay of the kind described in the paper or to short out the arc-suppression coil by an earthing resistor with an automatically operated switch. I think the use of the relay has advantages and that there is less likelihood of introducing unwanted surges than by short-circuiting the arc-suppression coil.

From the safety aspect, a line lying on the ground may often be touched without serious injury while the system is operating with the arc-suppression coil in circuit, but on the other hand if an earthing switch is closed and a comparatively high current is passed through the earth fault, anyone unlucky enough to touch the conductor at that moment will be electrocuted. The switching out of the faulty section by means of a wattmetrical relay has therefore the advantage from the safety angle.

I hope the authors will continue their research with a view to developing a relay which will give selective clearance on double earth faults, allowing the largest systems to be used with continuously-rated arc-suppression coils, thus obtaining the maximum degree of continuity of supply.

Mr. M. Kaufmann: I was connected some eight or nine years ago with the earliest applications in this country of British-made sensitive directional relays to compensated systems. Prior to that some German relays had been applied in this country; but neither type was an unqualified success. The reasons for this are fully explained in the paper, which fills in many details only dimly discernible at the time the first tests were made. Those early relays are still being used in circumstances similar to, and some even under conditions more onerous than, those in which the relays gave a rather indifferent performance. Some of these relays are being used to give indications of transient, as well as persistent, faults, though their use to trip faulty circuits is less common.

What has changed, as the paper makes clear, is our knowledge of the effect of the current-transformer characteristics on relay performance, and of the current distribution in the primary system under widely different fault conditions and power-system interconnections. The main difference between the conditions presented respectively to a relay required to operate and one not required to operate is a few degrees in the phase position of the relay current with respect to its voltage. Add to this that the non-operating relay receives a very large current and the operating relay only a minute one, and it is evident that success or failure can be decided by a small phase error in the associated transformers.

The performance is also affected by ratio errors and by the effect of under- and over-compensation in the suppressor. It is not surprising therefore that, as the authors have found, the difficulties can sometimes only be resolved by artificially increasing the active loss component of the suppressor. Personally, I am in sympathy with Mr. Lane's preference for short-circuiting the suppressor on persistent faults and using conventional discriminating relays.

Mr. E. W. Hill: On the question of the relative merits of direct paralleling of equal-ratio current transformers as compared with the use of summation transformers, there would seem to be, from the references in Section 5.3 and the last two paragraphs of Section 10 some contradiction between the authors' conclusions and those recorded by Mr. Shotter and myself in Section 12 of our paper "Current-Transformer Summations" read before this Institution* 13 years ago. These opposing conclusions were derived from tests in which the conditions differed in some material respects from those in the present authors' work, thus affording a possible explanation for the divergence. For example, our summation transformer had separated primary windings, three 10-amp primaries, one 5-amp secondary and 550 total ampere-turns; whereas the authors' transformer had intermingled windings, three 1-amp primaries and one 1-amp secondary, and 900 total ampere-turns. In our tests the secondary burden was low, under 2 VA; theirs was rather high, 30 VA. Furthermore, our test-set was connected to the secondary of one active current transformer, whereas the authors' was connected to the secondary of the summation transformer. The difference in the location of the test-sets is, of course, of paramount importance. Judging from the authors' references and those on pp. 151–152 of Dr. B. Hague's book "Instrument Transformers," I think it is possible that Section 12 of our 1931 paper has been misconstrued. In order to clear up the matter, Mr. Shotter and I intend to carry out further experiments and to communicate the results in due course to The Institution.

Dr. P. F. Stritzl: One fairly important aspect is not mentioned in the paper, namely whether transient faults should be indicated. Those in favour maintain that any trouble on the system, however short in duration, should be indicated. Those against such indication consider that there is no need for it and that it unnecessarily distracts the attention of the engineers on duty. What is the authors' opinion?

The current transformer is responsible for nearly all trouble experienced with the type of relay under consideration. In Fig. 12 the authors give some very useful information as to the

* *Journal I.E.E.*, 1931, 69, p. 1251.

permissible angle error. Unfortunately the curve refers to one particular voltage and a particular current-transformer ratio. It would be more useful still if the authors could give a curve or a family of curves generally applicable also to 11-kV and 33-kV systems and, if possible, to various current-transformer ratios.

What is the authors' opinion on the approximate angle of error found in current transformers now usually employed on 11- and 33-kV systems? Section 5.5 states that the core-balance transformer is a complete answer to the problem if multi-turn-primary current transformers are impracticable, and that on 6·6-kV and 11-kV systems this method is of considerable value. This should be qualified, as core-balance transformers of inadequate core section may have excessive angle errors. They can, of course, be compensated by resistors R_1 and R_2, as shown in Fig. 13. In practice this adjustment must be made, I think, by means of an actual earth-fault test; or do the authors advise the testing of existing current transformers in the manner shown in Fig. 17?

The paper refers only to induction-pattern relays; if dynamometer-type relays were used a capacitor would take the place of the resistor. The arrangement shown in Fig. 9 is open to some objection, as any graded scheme on ring mains would only be applicable under specific conditions. I think this would not apply if the relays were used only for indication, as there is no need then to shift the phase artificially in station Q.

In the last paragraph, the authors mention double-earth-fault discrimination. Some details on this point are desirable, as such discrimination is becoming increasingly important.

Mr. P. Mathews: The authors confirm the conclusion we reached some years ago that this protection is very largely, if not principally, a matter of correct current-transformer design. Hence producing a successful scheme using a 66-kV bushing transformer is a remarkable feat, especially as the authors trip breakers selectively in the manner usually associated with more common forms of protection.

Some years ago we installed a scheme of this kind on an 11-kV system. We did not include breaker tripping, but left the operating staff to make dispositions consistent with maintenance of supply as required, e.g. by opening a ring main at one point, etc. The system comprised a mixture of cable and overhead lines, and there were variations in the power factor of the relay operating current as noted by the authors in Section 3. Experience gained endorses the author's views on fault settings and permissible phase angles given in Section 8, and confirms that to obtain sufficient torque in the relays on faulty feeders without prejudicing correct operation on healthy ones, and vice versa, is a question of current-transformer design.

The authors' vector diagrams include both (*a*) the capacitance current which flows under normal conditions, and (*b*) the extra portion which flows under earth-fault conditions. All this has to be taken into account because current transformers have resistance, but the user is only concerned with (*b*), since it is only this that appears in the relay, and if the designers have been successful (*a*) is eliminated. The flow of (*b*) is shown in Fig. A, where a virtual voltage V_0, numerically equal to the phase voltage, is applied to all three phases in parallel at the fault point, and causes a flow of zero-sequence current as indicated.

Relays at E and F operate at unity power factor as the arc-suppression coil reduces the fault current to residual loss current only; but as there is a flow of current through the feeder admittance y to earth, a relay such as A beyond y, say at the busbar end of the feeder, will be carrying a corresponding amount of inductive balancing current, and so on for more complicated cases. This simplification is of considerable value in considering what primary currents, etc., will be available in any given project,

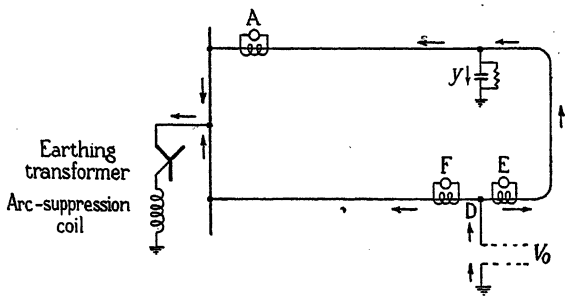


Fig. A

as only a single-phase diagram is necessary to deal with zero-sequence currents.

Obviously on a radial feeder with a fault towards the far end, the loss current of the part between the relay and the far end contributes nothing to the operation of the relay, but it is interesting to note that if the suppression coil is exactly in tune and the loss angle α of the system (i.e. of y) is uniform, a phase-angle error of α in the current transformer, etc., will give the effect of replacing the missing loss current, and relays at all points of the feeder will experience the same operating power, i.e. the total losses of the system and coil together. On a healthy feeder under the same conditions, the operating power will be zero, and this is the limit pointed out by the authors if wrong indication on healthy feeders is to be avoided.

On an interconnected system where there are two or more parallel paths, the total losses even under these theoretically ideal conditions will be divided by the number of parallel paths. The authors dismiss this rather lightly, since the required relay-operating power must be not greater than $1/n$ of the total system losses including the coil, where n is the number of parallel paths. Even where switch tripping is employed n may be equal to 2.

Mr. A. J. Ruddock: The principle of automatically disconnecting a faulted line section after a predetermined time interval is desirable when by virtue of system interconnection this can be effected without disturbing the supply to consumers, especially on the higher voltage systems where a high margin of insulation cannot be economically provided. The scheme evolved by the authors provides a valuable extended form of graded time discrimination without any of the disadvantages usually associated with high time settings.

On rural systems where protection and switchgear are elementary in character, sections between main substations cannot be so isolated under fault conditions without disturbing the supply to the many small substations *en route*; thus sustained coil operation is essential to permit that faulty section to be manually sectioned-down by aerial switches and the like until the faulty piece is eliminated. The essential aid for this process is the indicating relay, and in the past six years the N.S.S. (B.T.H.) relay has been successfully employed for this purpose. Having a minimum setting of 0·03 amp on a 90-amp system with a 7% in-phase component, indication has been most reliable on the radial feeder distributors; experience has shown that under ringed conditions a 10% in-phase fault component is desirable to give decisive action on all relays. This is being accomplished with the commissioning of a second coil to work in parallel with the present unit.

Dr. E. Billig: In Section 3 the authors state that there is no resonance in systems protected by Petersen coils at the time of an earth fault. However, as soon as the fault is cleared or the faulty feeder disconnected, the neutral point and with it the whole system does oscillate at a frequency of nearly 50 c/s, if properly tuned. Resonance voltages of a dangerous magnitude might thus occur whenever a zero phase voltage was imposed on the

system, owing for example to some asymmetry in the three phases.

When Petersen coils were first put into service on the Continent, resonance troubles were frequently encountered. Overhead lines not properly transposed, or internal faults in one phase of a transformer, were the most common sources of the trouble, giving rise to high resonance voltages. The design of Petersen coils was subsequently altered by working the iron core at such high densities that any tendency of the neutral voltage to rise to dangerously high levels would be suppressed by the core becoming saturated.

The authors express surprise at the slow rate of rise in errors when current transformers are operated at a very small fraction of their rated current. Actually current-transformer errors vary in inverse proportion to the permeability of the iron core and approach a constant value at zero current corresponding to the initial permeability which for Mumetal is fairly high.

As mentioned in Section 4, toroidal current transformers are usually astatic. When placed in an inhomogeneous magnetic field however, such as that due to the load current in an adjacent phase, a certain amount of flux is induced in the core as the field is stronger in those parts nearer to the current-carrying lead. This effect can easily be demonstrated by connecting a vibration galvanometer to the open-circuited secondary winding of a current transformer which carries no primary current, but is placed near a conductor carrying heavy current. The magnitude of the excitation due to current I can easily be derived as $-I(d/2D)^n$, where D is the distance from lead to centre of core, d the mean diameter and $n = 3$ for a round core, or d is the distance between limbs and $n = 2$ for a square core. The leakage field produced by symmetrical three-phase current in each one of the three cores is in phase with the current in the centre phase. Its influence on the errors becomes greater as the magnitude of the load current exceeds that of the single-phase current to be measured by the relay. This is evident from Table 5, where the errors with 60, 30 and 15-amp single-phase currents are practically the same in each test, and are of the same magnitude and phase as those of Table 3, Test 1, corresponding to 20, 10 and 5 per cent of 300 amp. For the lower single-phase currents the leakage field shifts the error and phase angle more and more, with the results depending in tests 1 to 4, on the phase relation between the single-phase current and the leakage field, which in turn is practically in phase with the load current in the centre phase, as explained above. According to the formula given, the load current of 300 amp will excite the current transformer in the adjacent phase with $-300(6\frac{1}{2}/2 \times 51)^3 = -0{\cdot}069$ amp. This additional excitation accounts quantitatively for all the changes in performance recorded in Table 5. It should be noted that 16 times greater effects would be expected if square cores had been used instead of round ones.

Mr. W. T. J. Atkins (*communicated*): The paper gives an admirable and exhaustive review of the electrical conditions which occur in a system earthed through a Petersen coil and affected by a single earth fault. The methods of exposition are remarkably clear, and, though suitable modifications are desirable for purposes of practical computation, they set out once and for all the quantitative principles controlling the design of fault-detecting equipment on such systems. The importance of this work is great, since we may confidently look forward to expanding applications of these methods in the development of protective technique. Again, the authors' investigations of the disturbing effects introduced by voltage and current transformations are a model of how to establish the *prima facie* practicability of obtaining response to the fault conditions in question, by relays operating on secondary quantities.

In these circumstances, it is disappointing to find the subject of final testing by artificial faults dismissed in two casual sentences. On the paper's own showing, some of the factors affecting the performance of the equipment are unknown—and sometimes even unknowable—as to their absolute magnitude and phase position, so that often there is no recourse other than an appeal to the ultimate overall test for commissioning adjustments. That, in fact, is the reason for the very important and valuable phase compensation provided in the relays and described in Section 9.2. Probably space limitations have prevented the adequate treatment of this matter, which deserved more prominence, but, in passing, it is worth drawing attention to the rare and fortunate circumstance that, with this special type of protective combination, testing by artificial faults causes no system disturbance and hence is easy and convenient as compared with the verification of most other protective devices.

A further question, which is ignored in the paper, concerns the effects of wave-form distortion. If the system-voltage wave contains harmonic components, the various capacitance and fault currents will contain corresponding components, magnified by the order of the harmonics. Although ideally these components should not modify the response of the fault detectors to any material extent, they might well in practice have a serious disturbing influence on induction-type apparatus. As experience shows that this effect can be of considerable magnitude, it would be of interest to know how the authors render their relays immune to it.

Mr. A. Burke (*communicated*): It is regrettable that the authors should have helped to perpetuate an approach to the subject which does not always lead to correct conclusions. The fundamental effect of a "dead" earth-fault is to superimpose on the existing voltages of all conductors a voltage to earth equal in magnitude but opposite in phase to the voltage to earth (prior to the fault) of the faulty conductor, at the point of fault. Assuming equal capacitances to earth, this voltage sends a current to earth from each conductor equal and opposite to that portion of the charging current of the faulty phase, which previously flowed to earth and which was neutralized by the corresponding currents from the other phases. This gives the same result as that shown by the authors as far as currents to earth are concerned, but an essentially different one for the currents in the individual conductors.

Taking the simpler case of a healthy feeder, the authors say that the result of an earth fault is to add to the existing positive and negative sequence currents a zero sequence current in two phases only. As is clear from above, the zero sequence current is the same in all phases. Thus, difficulty due to magnetizing idle transformers does not arise on healthy feeders (nor beyond the fault on the faulty feeder) and the example of a short faulty feeder with a residual current of only 2 or 3 amp is also inappropriate. The statement that this small current must provide magnetizing current for the healthy phases is misleading since, presumably, the test results for ratio and angle errors include this effect. The ratio error is in any case unimportant. The angle error may be greater, but its effect is much smaller, than with larger currents. For instance, 10 amp at an error of 1° changes the apparent active current by 0·17 amp as compared with 0·07 for 2 amp at an error of 2°. In both cases the true active component is the same. The angle error may in fact be decreased, depending on the resistance and reactance of the burden and whether there is over- or under-compensation.

With perfect tuning, all reactive current returns from earth via the Petersen coil and then flows along both the healthy and the faulty feeders, decreasing uniformly to zero at their far ends; it is equally divided between the three phases. With over-compensation there is, in addition, the excess current which flows out to the fault in the faulty phase only. The authors'

references to "busbars carrying Petersen coil current" apply only to this excess and to the active component; without this qualification the expression is misleading.

Again, the authors deal only with under-compensation in their diagrams, and it should be particularly noted that the deficiency current does not necessarily flow between the Petersen coil and the fault; it flows to all transformers and other apparatus which afford a path to the other phases, and divides between them according to the zero sequence impedance of their paths.

Mr. R. C. Cuffe (*communicated*): It is unfortunate that the authors' approach to the subject of this paper has been so compressed. Many points concerning the vector and schematic diagrams are by no means self-explanatory. Practically all papers published in English on the technics of systems equipped with Petersen coils merely scratch the surface of this rather complex subject, usually confining themselves to saying no more than what previous papers have already stated. The present authors are to be commended for doing more than that, but owing to the condensed nature of their paper it is feared that the relative importance of many points mentioned will not be properly appreciated.

The reasons given by the authors for the necessity of automatically isolating the faulty section of a system immediately are not quite clear. Possibly this view may have been influenced by the general long association with solidly earthed systems. Regarding their first reason, any insulation, which in operation has to withstand repeated half-minute applications of a given voltage, must surely be designed to withstand that voltage continuously. Perhaps the authors had in mind voltage transformers with some point of their winding earthed. The cost of replacing such transformers by others capable of withstanding line voltage continuously would not be excessive and would probably compare favourably with the authors' scheme involving many precision current transformers. As to the second reason, the danger to life of a fallen conductor is probably more apparent than real, except in the case of high resistances to earth when the correct operation of the authors' scheme may be problematic. Perhaps the authors could give some information on the operation of their scheme under such conditions.

If short-time tripping is to be utilized, why cannot the losses of the Petersen coil be increased considerably to give the twofold advantage of a cheaper coil and more watts available for operating the relays? Probably a less sensitive relay would then suffice. The scheme described appears to rely largely on the shifting of the voltage E_p to avoid the faulty tripping of healthy feeders. An essential with this arrangement is that the system shall be under-compensated. When a section of the system is disconnected automatically on the occurrence of an earth fault, then the system remaining will probably be left over-compensated. If a second earth fault occurred before the Petersen coil had been readjusted, it would appear that a general collapse of the system would ensue. Undoubtedly two consecutive earth faults may not be common, but under lightning conditions this can occur, and the practical difficulties of then ascertaining that the coil needs re-tuning (should a remote section trip) and of setting it to the correct value are not inconsiderable.

The figures given by the authors for the power factor of a healthy feeder are interesting. Perhaps they could indicate how these vary for systems of different voltages, and also the weather conditions both before and at the time measurements were made. If practical data have already been published on this, the references would be welcome.

Mr. V. Easton (*communicated*): In the opinion of many engineers, the chief advantage of earthing a system through arc-suppression coils is the possibility of clearing transient earth faults with a minimum of disturbance, rather than the ability to operate for an indefinite period with a fault on one line. The latter practice results in excessive stress on the system insulation and the possibility of interference with communication circuits, together with other difficulties. In these circumstances, the development of another type of relay to disconnect the faulty section after a few seconds delay is of much interest.

Considerable pains have been taken by the authors to obtain a relay sensitive to the comparatively small power component of the fault current. A high degree of accuracy is essential for the current transformers, and if applied to an existing system this might necessitate replacement of existing transformers. Such action might be avoided, if arrangements were made to increase artificially the power component of the fault current, by connecting automatically a resistor in parallel with the coil, should the fault persist for a given period. Such a scheme has frequently been adopted, the fault current with the resistance in circuit being sufficient to cause operation of normal earth-leakage or over-current relays.

In some circumstances, the comparatively high fault current necessary to operate such relays may be considered undesirable, but even so there would be no objection to increasing several times the minimum power loss given in Section 8.1.1, thus permitting a less sensitive setting of the relay. A somewhat similar arrangement has been contemplated by the authors in Section 12, and it would be interesting to learn the increase in the active component under fault conditions which has actually been required.

Mr. G. Minter (*communicated*): Of the various methods of dealing with a sustained earth fault on a system protected by a Petersen coil, the one described by the authors restores the protection of the coil to the healthy part of the system in the shortest time and with the least disturbance. The advantage is a very real one during severe thunderstorms, when a sustained fault on one part of the system may be followed, after a short interval, by a transient fault on another phase and on another feeder. It may mean the difference between losing one feeder and losing two feeders, and the loss of two feeders on a ring-main system may involve a considerable interruption of supply.

The method of short-circuiting the Petersen coil in the event of a sustained fault can only compete, in this respect, with the method described by the authors, if means are also provided for the automatic re-opening of the short-circuiting switch after a sustained fault has been cleared. In spite of this and other advantages, the wattmeter-type relay is not likely to be used extensively on existing systems, unless it can be used with existing current transformers and can confidently be left in commission after a small number of tests have been carried out in order to check connections, etc.

If any doubts exist regarding the behaviour of the complete protective equipment, tests must be carried out which, owing to the number of variables involved and the problem of providing observers and telephonic communication, are very difficult to stage.

It appears, however, that if a relay imposing a negligible burden on the existing current transformers could be used, it might be possible to reduce the overall errors to a level comparable with those given in Table 6. There is at least one design of thermionic relay which appears to be suitable and which includes only one valve; current flows in the anode circuit only while fault conditions exist, and experience shows that this valve gives very satisfactory service when working under similar conditions. I should like to know whether the authors consider that the errors would be reduced to the levels cited in Table 6 if such a relay were used in conjunction with typical 150/1 bar-primary protective current transformers. The Petersen-coil current is approximately 50 amp, and the current transformers, used exclusively for the purpose, could probably be balanced, to some extent,

for positive and negative phase-sequence conditions by primary injection.

In Section 8, the authors refer to operation of the relays on incoming feeders at substations supplying healthy portions of the network, and state that this is avoided by a phase shift on relays on incoming feeders. Since most feeders on a ring-main system become incoming feeders under certain conditions, it seems unlikely that this is a remedy which can be applied indiscriminately, and it appears preferable to reduce the sensitivity of all relays at very low leading power factors. This, of course, could be done very easily with a thermionic relay.

The authors refer in Section 11 to troubles due to contact resistance at the point where the three transformer leads were paralleled. Do they recommend that all current-transformer secondary connections should be sweated when used on this type of protection?

Mr. J. J. O'Doherty (*communicated*): Sensitive wattmetric relays for indicating faults on arc-suppression systems have been in successful operation for at least 15 years. The use of numerous vector diagrams to explain the elementary features of operation of this simple relay is very tedious. An approach which may make a wider appeal is obtained by considering only the active, as distinct from reactive, power which operates the relay. The equivalent single-phase circuit formed by the earth and the transmission-line conductors continually dissipates energy which it must receive from some power source. The obvious source is the prime mover driving the three-phase generating plant, and a real transformation of active power from three-phase to single-phase must take place at the earth fault. Thus, the operation of the relays can readily be visualized by picturing a single-phase generator at the fault and ignoring three-phase generation.

The statement that the permissible difference between I_P and I_{C3} depends on the characteristics of the coil and the system voltage is somewhat wide of the mark; it would seem better to say that the permissible out-of-balance depends on the rate of rise of restriking voltage in the circuit.

Considering the general use of the tripping scheme put forward by the authors, it is quite clear that there are practical factors which will render it unreliable in particular systems. Two such factors which the authors have not referred to are (*a*) variation in conductance over insulators, and (*b*) high-resistance earths on system with unearthed cross-arms.

Some fault statistics for the system described would be greatly appreciated.

Mr. W. Szwander (*communicated*): Earth-fault relays in Petersen-coil protected systems are necessary because some earth faults are persistent. Even when system insulation makes possible a sustained operation with one phase earthed, at least a positive indication of the faulty section is necessary, in all but very simple systems, to enable a speedy restoration of normal operational conditions. When system insulation is not adequate for operation of any duration under fault conditions, sustained earth faults must be quickly localized and isolated. For this purpose, the Petersen coil is short-circuited in many systems in this country, so as to initiate the operation of the system short-circuit protection.

The system of protection described by the authors represents a much better solution of the problem, because it avoids creating the undesirable short-circuit conditions in the system, with the associated heavy duty on oil circuit-breakers, with increased damage at the fault spot, etc. Even when system insulation is high enough for sustained operation with displaced voltages, such operation ought to be avoided, because of the potential danger arising with a second earth fault. For this purpose discriminative protection as described in the paper is very useful.

This kind of protection has been employed on the Continent for over 15 years, particularly for underground systems, where earth faults in cables cannot be left too long without isolation. It is worth stressing that, when applying the system described, besides all the difficulties caused by the extremely high sensitivity requirements, there is also the great advantage of not being restricted by any limitations concerning the speed of relay operation. Excessive requirements regarding relay sensitivity and current-transformer performance can be avoided by artificially increasing the Petersen-coil losses during the time of relay operation. This can be done, e.g., by a secondary winding on the coil, and by loading this winding with a suitably dimensioned resistance, after a time equal to the lowest relay time-setting. The provision of an automatic switch for the purpose is well worth while compared with the gains achieved by easing the duty of protective current transformers and relays.

There are some minor inconsistencies in Section 3 of the paper. In Fig. 2(*b*), the fault-current consists of the components I_{CW} and I_{PW} not when the currents I_P and I_{C3} themselves are equal, but when the reactive components of these currents are equal. It is not correct to say that "actually there is no resonance" at the time of earth fault; in my opinion, there is here a typical case of current resonance, because the voltage feeding the capacitance and the inductance have a common component, namely the e.m.f. of the faulty phase.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. L. B. S. Golds and **C. L. Lipman** (*in reply*): We shall first deal with two subjects which appear to be of general interest, and then reply to contributors individually.

Application of the Equipment.—Messrs. Lane, Leyburn and Kaufmann favour short-circuiting the coil through a resistance after which the normal earth-leakage protection should operate, while Messrs. Bird, Ruddock, Minter and Szwander appreciate the advantages of isolating the faulty feeder with the equipment described in the paper. The first method has already been used extensively, but it causes a power arc at the fault when the resistance is switched in, which may cause a phase-to-phase fault and will in any case cause more damage than the residual fault current with the coil in circuit. More details of the faults mentioned by Mr. Lane, which were cleared by other protection, would have been interesting. Moreover, with high-resistance faults it is difficult to make ordinary earth-leakage relays operate at all. Those who favour isolation with the coil still in circuit, retain the advantages of Petersen-coil protection during the whole period of the fault and immediately after it. We should perhaps mention that it is usual to run the system normally under-compensated in order to avoid excessive over-compensation after isolation and until the coil is readjusted.

Current Transformers.—There seems to be an impression that high-accuracy current transformers are essential in all cases, but this is certainly not so, and the allowable errors can be easily worked out from the formula in Section 6.3 to meet various system conditions. Messrs. Ruddock, Mathews, Kaufmann and Ayres have satisfactorily operated the system for indication with Stalloy-cored transformers, although their success may be due mainly to fortunate circumstances. We are, however, aware of instances where the transformers have not been quite good enough to deal with the impedance of the particular relay in use. The design of relay described in the paper was adopted on account of its high inherent efficiency resulting in a low VA burden on the transformers. Compared with the cost of the rest of the gear, that of the protective equipment is not excessive.

Mr. Ayres.—The fact that the capacitance and reactance currents are drawn from different phases does, of course, tie the voltages, but we wished to make the point that the sources of the two currents are not the same, and that the only common portion of the capacitance and reactance circuits is the fault and the faulty phase at the time of a fault.

We are indebted to Mr. Ayres for pointing out the error in the power factor of the coil which has now been corrected, and also for drawing attention to the semi-conducting glaze insulators which would increase and stabilize the angle α, and thus enable less accurate current transformers to be used. These insulators appear to us to have most desirable features from the point of view of this equipment.

Mr. Lane.—The voltage transformer has not been the major source of trouble in obtaining satisfactory relay operation. We should add that five-limb transformers with the auxiliary windings on the two outer limbs have been found to have a phase-angle change of over 60 min for a voltage variation from 90% to 115% of rated primary voltage, and are not equivalent to a broken-delta winding, the use of which we would certainly recommend. A type test on a transformer with a broken-delta winding is given in Table A.

Table A

RATIO AND PHASE-ANGLE TESTS* ON THE BROKEN-DELTA WINDING OF A 66-KV 5-LIMB VOLTAGE TRANSFORMER. RATED BURDEN 200 VA.

Test 1. *Test at* 15 *VA Unity Power-Factor Burden*

Phase	A		B		C	
Percentage voltage	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)
80	1 −	0·5 +	1 −	0·5 +	2 −	0·4 +
100	1 +	0·4 +	0	0·4 +	0	0·3 +
115	3 +	0·3 +	2 +	0·3 +	2 +	0·2 +

Test 2. *Test at* 200 *VA Unity Power-Factor Burden*

Phase	A		B		C	
Percentage voltage	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)
80	3 −	0·2 +	3 −	0·2 +	3 −	0·1 +
100	2 −	0·1 +	2 −	0·1 +	2 −	0·1 +
115	0	0·0	0	0·0	0	0·1 −

Test 3. *Test with* 1 *Wattmeter-Type Relay Voltage Circuit as Burden*

Phase	A		B		C	
Percentage voltage	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)	Phase angle (min)	Ratio error (%)
80	0	0·5 +	0	0·5 +	0	0·4 +
100	3 +	0·4 +	2 +	0·4 +	2 +	0·3 +
115	4 +	0·3 +	4 +	0·2 +	4 +	0·2 +

* These tests were made by supplying the transformer under test by means of a delta/star transformer with the star point brought out. For determining the ratio and phase-angle errors, each leg of the transformer under test was short-circuited in turn and the primary reference voltage was the voltage of that phase which was short-circuited.

Mr. Bird.—The term "Petersen coil" was perpetuated partly because "arc-suppression coil" does not fully describe the coil's function, and partly because it is not unusual to name pieces of apparatus after their originator. Also, as the paper was intended as a sequel to that by Messrs. Willott Taylor and Stritzl, we felt that the coil should bear the same name.

We are glad Mr. Bird referred to the safety aspect as a reason for the application of the equipment; this is particularly important on high-voltage systems.

Mr. Kaufmann.—The small angle which may sometimes differentiate between a relay which should operate and one which should not, was one of the reasons for the indifferent performance of the early relays. However, once the system is thoroughly understood, we then know what degree of control must be exercised over phase-angle errors to give discrimination.

Mr. Hill.—Messrs. Hill and Shotter's test results given in their paper in 1931 have undoubtedly been misinterpreted, and it was to clarify the matter that we made the tests described. We felt, too, that this was unfair to Mr. Shotter's valuable pioneering

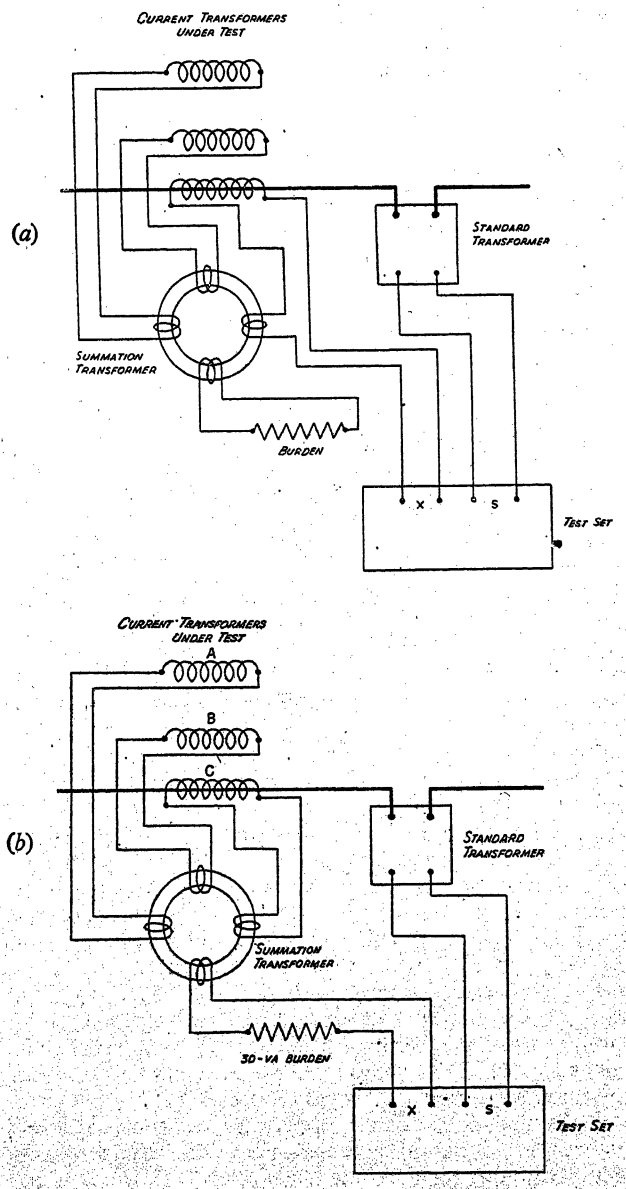


Fig. B

work on the subject. It should perhaps have been pointed out in the paper that the Hill and Shotter tests were made with the test set in the main current-transformer secondary circuit shown in Fig. B(*a*), whereas ours were made with the test set connected in the summation-transformer secondary shown in Fig. B(*b*). We obtain of course similar figures to them when the test set is connected as shown in Fig. B(*a*); we shall be interested to see the results of their further experiments.

Dr. Stritzl.—It would certainly be useful if transient faults could be indicated at attended substations, where the flag indicator could be reset immediately; but we see disadvantages at unattended stations, as a wrong indication of a persistent fault may be given if the engineer is unable to reset the indicator frequently. We have known cases of this occurring.

The current transformers on existing gear vary in performance to such an extent that it is impossible to give a direct answer to the question. Usually the core section of core-balance transformers is not a limiting factor, and if the transformer is made with a Mumetal core we believe the errors will be small enough to give satisfactory results on 6·6- and 11-kV schemes.

Mr. Mathews.—Mr. Mathews's simplified diagram is of interest, but we think it is supplementary to, and not a substitute for, the basic principles outlined in the paper.

Mr. Ruddock.—We are grateful to Mr. Ruddock for stressing the value of the relays in eliminating the objectionable, long time delay with maximum fault current flowing, which occurs with solid or resistance earthing. His scheme illustrates the utility of this type of protection. Had he used a more sensitive and lower impedance relay, he would not have had to wait until a second coil was added to obtain reliable indication when the system was interconnected.

Dr. Billig.—In Stalloy-core transformers the error increases rapidly as the load decreases, but as indicated in the paper there is a marked improvement by using transformers with Mumetal cores.

We have tried connecting the vibration galvanometer as suggested, but the impedance of the instrument vitiates the results, and accordingly we think that our tests, which are confirmed by Dr. Billig's formula, offer the best proof of the interaction between neighbouring conductors and current transformers. We hope to see the complete development of Dr. Billig's proof published in due course.

Mr. Atkins.—Mr. Atkins's remarks are much appreciated. Like him, we also were very disappointed in not being able, owing to space considerations, to publish details of commissioning and testing.

We have examined the effect of harmonics, but owing to the small percentage of harmonics in the voltage wave the effect of the proportionally greater percentage in the current wave is negligible, especially as this is an induction type of wattmeter movement.

Mr. Burke.—There appears to be some misunderstanding of our explanation of the circuit conditions and the vector diagrams. We can assure Mr. Burke that the vector relationships of the voltages and currents were very carefully checked with a phase-angle meter. The arrows in Figs. 1(*a*), 2(*a*) and 3(*a*) merely indicate the instantaneous current flow; no attempt was made to line up the vector diagrams.

His statement that the Petersen-coil current flows along both the healthy and faulty feeders under exactly compensated conditions is wrong. We demonstrated the fundamental circuit at the meeting, and think this would have convinced Mr. Burke of the fallacy of his statement. If he will make some measurements he will find that all the losses in the coil and capacitance currents sum in the fault and the faulty phase.

Mr. Cuffe.—In the original draft of the paper additional diagrams were included which would have clarified some of the points which Mr. Cuffe had in mind; these, however, had to be omitted. We agree that a more detailed analysis would have improved the explanation, but we would refer him to Mr. Doherty's communication to show how difficult it is to satisfy all concerned.

In the case given in the paper, certain apparatus was stated by the manufacturers to be only suitable for operation at the increased voltage for a definite length of time in any period. This was one reason for the introduction of the protective gear.

Fallen conductors on 66-kV systems can very easily cause a fatality, while a high-resistance fault can also occur on solid and resistance earthed systems and will not operate the protective equipment. The voltage at which the relay will operate depends very much on the active component of the current at the point at which the relay is installed.

Temporary artificial increase of the coil losses, suggested by Mr. Cuffe and Mr. Easton, by the introduction of a resistance is useful where it is required, but it should be no more than is necessary to give positive operation of the relay, and it should not increase the value of the fault current sufficiently to prevent the extinction of the arc or to cause burning of the conductor.

Mr. Easton.—If the insulation is adequate on 11-kV systems, there is no objection to operating the system with a fault for an indefinitely long period, but in our opinion indicating relays to locate the fault without disconnecting the feeders should be employed. On cable systems one Mumetal ring-type transformer on the cable is all that is required and is inexpensive.

Mr. Minter.—The difficulties of testing are not so great as may be imagined, as no shut-down on the system is normally required. A thermionic relay may be a development of the future, but we have no details of the burden on the current transformer. If the burden could be reduced to 15 VA, we see no reason why the scheme embodying a thermionic relay should not work on typical 150/1-amp current transformers, although we find that their performance varies widely owing to switchgear design considerations.

With regard to the contact resistance of the current transformer connections, it is not essential to sweat the leads providing care is taken, but it would be advisable to carry out a type test using the switchgear wiring. We employed the special sweated connections in order to obtain reliable and consistent results for publication.

Mr. O'Doherty.—We would refer Mr. O'Doherty to our reply to Mr. Mathews, who is also in favour of the single-phase explanation.

A high-resistance earth fault, as on other systems, is a condition under which the scheme fails, but it will operate satisfactorily with a voltage across the coil as low as 50%. Further information is given in Paper No. 319 presented at the International Conference on Large High-Tension Electric Systems, 1939, in Paris. Variation in leakage current over insulators can generally be overcome on the phase adjustment provided, if it is made for the worst conditions initially.

Mr. Szwander.—With regard to the resonance controversy we would refer Mr. Szwander to our reply to Mr. Ayres. Although, as Mr. Szwander states, this system has been in operation for 15 years on the Continent very little detailed information has been available. Certainly no comprehensive paper has been published, but Dr. E. T. B. Gross of Cornell University has drawn our attention, since our paper was published, to a paper of his* which gives a number of references dealing with various aspects of the subject.

* *Transactions of the American I.E.E.*, 1941, 60, p. 968.

"THE CONSUMER'S SUPPLY CONTROL UNIT OF THE FUTURE AND ITS EFFECT ON THE DESIGN OF THE ELECTRICITY METER"

MEASUREMENTS SECTION DISCUSSION MEETINGS

Explaining the background of the two discussion meetings of the Measurements Section at the first meeting on 31st March, the Secretary of The Institution pointed out that about three years ago discussions on post-war problems were held with the then Ministry of Works and Planning and a number of bodies, all of which had started work on post-war planning in their own particular spheres. The Institution had set up its own post-war planning organization, and, on the invitation of Lord Reith, the Council consented to act as convener of the Electrical Installations (Study) Committee. A first draft Report was prepared by this Committee and was followed by a final Report. This will be issued as No. 11 of the series being published by H.M. Stationery Office under the general title of "Post-War Building Studies." In the meantime, the codifying of requirements for new buildings had become so urgent that the Council, realizing the difficulties entailed by further delay, felt it desirable for the Measurements Section to discuss one aspect of the matter.

FIRST DISCUSSION, 31ST MARCH, 1944

The first discussion was opened by **Mr. E. Fawssett** and **Mr. G. F. Shotter.**

Mr. E. Fawssett said there was general agreement on the national need for tidying up and simplifying consumers' service gear. This was largely bound up with standardizing the relative positions in space of (*a*) incoming service terminals; (*b*) meter terminals; and (*c*) consumer's main switch terminals. With no standard at present existing for any of these, and with several makers of each component, this ideal could not be reached immediately, but, given goodwill and co-operation, there was no inherent reason why it should not be reached quickly.

Postulating that standardization of this sort could be applied to a very large proportion of the forthcoming new houses and that their needs could be met by, at most, two general layouts, the possibility of proceeding in two stages was suggested, as follows: (*a*) using existing apparatus to form the neatest possible assembly, by wiring the necessary connections and then covering them in; and (*b*) having standardized the position in space of the meter terminals, to devise a moulded connecting block between these, the incoming service terminals and the consumer's switch—all concealed, shock-proof, and thief-proof. It was stressed that there was more small (and unnecessary) variation in the meter terminal arrangement than in any other detail, so that this feature called for first attention.

Very helpful designs for a neat layout had been prepared by several E.D.A. Area Committees; the Study Committee had sifted them and submitted two schemes, the first for use at once —using existing apparatus—and the second as a more ideal arrangement needing final development.

Mr. Fawssett drew attention to the exhibits at the meeting and described their salient features. In the first exhibit, he felt that by putting the meter at the top and the switch below the fuses, an unnecessary crossing of wires occurred, thus departing from even a temporary solution. Another scheme also used existing apparatus and housed it in a presentable cabinet, thus creating an article of furniture which could be placed even in the front room of a cottage. It measured 4 ft by 1 ft, and could be recessed if desired. He had heard criticisms of such a large panel, while the Study Committee itself did not like its own first arrangement or the large cabinet. Personally, he did not like the Committee's "ideal" arrangement, as the meter was not readily accessible. Moreover, the meter was on the right, which meant either crossing the connections or having non-standard connections.

On some of the E.D.A. proposals, he said the Northern Counties' Area showed a neat arrangement which was meant to be let into the wall, but he did not think maintenance engineers would favour it. It measured approximately 18 in by 12 in.

The Mid-East Area had designed a very attractive unit which appeared to be the best layout for avoiding crossed connections or a departure from the present B.S. terminal sequence. The whole gear, including consumer's circuit fuses up to 6 in number, occupied an 18 in by 15 in board, and had cartridge fuses which could be replaced by the consumer at a moderate cost. This design required the standardization of all the terminals involved, but it was the ideal to aim at. There was, however, no provision for a check meter, and he was advised that the Electricity Commissioners regarded such a meter as necessary. Mr. Fawssett showed three sketches indicating the necessary development of the moulded-block idea to admit the introduction of a check meter when required. Finally, he referred to the plug-in meter and showed a very neat arrangement devised by the engineer of Edinburgh Corporation.

Mr. G. F. Shotter discussed a matter which he regarded as of the utmost importance, namely the best load/accuracy range of domestic electricity meters. By "load/accuracy" range was meant the range from the lowest B.S. load to the highest load which could be accurately carried continuously by the meter to within, say, the limits of the present B.S.S. It was well known that two load ranges existed under the present B.S.S.: (*a*) 5% to 125%, (25 : 1), and (*b*) a long range of 5% to 200% (40 : 1). The Americans went even farther by catering for an 80 : 1 range.

If the load range of various kinds or types of domestic load were known, it would be possible to determine not merely the load range of meters, but also the number of sizes required. It had always been his opinion that the 25 : 1 range was too narrow to record many of the domestic loads accurately. The B.S. long-range meter did not go far enough, but the 60 : 1 range appeared to meet many of the cases which had been investigated.

He emphasized that if meters were installed which were much too large, this would cause an overall loss much greater than appeared from the percentage error usually stated as being permissible, the actual value depending on the type of meter, wear of bearings, etc.

Finally, before any discussion took place in connection with the revision of B.S.37 as to whether the 2½-amp meter should continue in use or whether the short-range meter should continue side by side with the long-range meter, the subject should be investigated scientifically, first as to the ranges and character of domestic loads, and secondly as to what range and sizes of meter were required to cover these ranges under the existing conditions.

In the ensuing discussion, it was made clear, as an extension of what Mr. Fawssett had said, that the consumers' units envisaged by the Study Committee were intended for the "Council"

or subsidy-type of post-war small house, and Mr. J. W. J. Townley, as Chairman of a Panel which was also studying the matter, asked for criticisms of the exhibits and for general comments, for the guidance of that body. It was hoped to arrive at a unit which was practicable, inexpensive and suitable for the purpose for which it was intended.

Some speakers did not share Mr. Fawssett's optimism as to the possibility of reaching agreement on standardization, the "rugged independence" of supply engineers being regarded as an obstacle. However, some degree of uniformity was hoped for. The importance of the problem had prompted some supply authorities to take immediate steps, hence production of the units exhibited was likely with an eye to the immediate post-war period, although one London supply authority's representative said frankly that he could not wait until a decision was reached on a standard unit. Indeed, steps were being taken for one of the units designed by this speaker to be put into production as soon as possible.

It was pointed out that, even if standardization of dimensions was agreed upon, there would still be millions of existing meters which had a long term of useful life before them. Against this it was emphasized that these would have to wait and that the immediate problem was to deal with the type of house referred to by Mr. Townley. A hinged cover on these units was asked for, and among those who desired to make them sufficiently presentable to be placed in a conspicuous position in the house was one speaker who suggested putting a mirror in the cover.

Opinions differed as to the desirability of recessing the units and putting them on the surface of the wall, those advocating the latter calling attention to the increased accessibility of this arrangement. Again, for the type of house in mind, varying views were expressed as to the desirability of exceptionally long-range meters, and there were also different views as to the need for having anything other than shilling slots in prepayment meters.

One provincial supply station engineer said he and all supply engineers should be thoroughly ashamed of themselves for what they had permitted hitherto in the matter of untidy circuit-control arrangements on consumers' premises; even the worst design among the exhibits was an advance on anything accomplished in the past.

The manufacturers, it was emphasized, were anxious to give the electrical industry what it wanted, but another speaker said that among the 20 or more supply authorities in the London area it had so far not been found possible to get agreement on standardization. Any plans made should include methods of tidying up existing installations as and when this became possible. Various suggestions were made for improving the design on view, and it was arranged that the exhibits should be placed at the disposal of the Panel studying the problem.

SECOND DISCUSSION, 14TH JUNE, 1944

Since at the first Discussion Meeting time had prevented the meter side of the problem, introduced by Mr. Shotter, from being adequately discussed, it had been decided to hold an additional meeting, so that both Mr. Shotter and Mr. Fawssett—the latter represented on this occasion by Mr. C. W. Hughes—could recapitulate their original points and amplify them.

Mr. G. F. Shotter, in extension of his previous remarks, said that an ever-present difficulty when metering the wide range of domestic loads, was the choice of a meter having a loading range sufficient to cover that of the domestic load to be measured, and having the specified accuracy throughout this range. At one end of the domestic load range there was the purely lighting consumer with, perhaps, a bowl fire, radio set and an electric iron, whilst at the other end there was the "all-electric" consumer with a connected load in the neighbourhood of, say, 25 kW. The ideal from the metering point of view was that all loads, including the lowest, should be accurately measured, if possible by one meter. Fuller knowledge of the load diversity of domestic supplies would be of advantage, not only for the correct choice of meter, but also to permit a more scientific approach to the number of sizes required.

In the all-electric house, high peak loads of short duration occurred, whereas other apparatus, such as clocks, ran for 24 hours a day, and refrigerators intermittently for the same period. It was in an endeavour to cover this wide range that the so-called long-range meter was developed, and it was sometimes overlooked that the establishment of such a design might be the means of reducing the number of sizes required.

Experience indicated that a range of 25 : 1 was not sufficient to cater for normal domestic loads. The use of a meter with, say, a range up to 300 per cent normal load not only gave more tolerance in the selection of the rating but also conduced to a more accurate registration of the lower loads.

It should be noticed that if a long-range meter were used, the normal 2½-amp instrument would allow peak loads up to 7½ amp to be recorded. This size of meter would seem to cover a large number of flats and cottages in rural areas where lighting, and perhaps an iron and a wireless set only were connected. The 2½-amp meter had been the subject of considerable discussion in the past, but even if the industry considered this size unsuitable, there was no doubt that the 5-amp long-range meter could not be dispensed with.

Another difficulty was the problem of the prepayment meter where the capacity of the combined equipment was limited by that of the switch.

Mr. C. W. Hughes recapitulated the points raised by Mr. Fawssett at the previous meeting and put forward certain other points of his own for discussion.

Referring to the supply control units which had been shown on the previous occasion, and to the additional exhibits at this meeting, he said it had been assumed in designing these units, which were intended for dwellings serving lower-income groups, that the tariff would be such that only one meter—either quarterly, flat-rate prepayment or two-part-tariff prepayment—would be required. The meter was the most awkward item to fit neatly into the assembly, as at present there was no standard as to overall size, fixing centres or terminal-block dimensions. So far as quarterly meters were concerned, there were indications that the manufacturers, despite many difficulties, were prepared to effect some measure of uniformity, and it was essential that such standardization as was applicable to the prepayment meter should follow in due course. In this meter, the centres of the fixing holes should be fixed relative to each other; the terminal block should be standard and the same as that of quarterly meters; the position of the terminal block relative to the fixing centres should be standard; the coin slot should be on the front of the meters and the maximum rectangular volume needed to contain any meter should be known. Unless this measure of standardization were obtained it was almost impossible to design a satisfactory consumers' control unit.

Silhouettes of the outlines of eleven prepayment meters were exhibited; no two were shown to have the same shape, and very few were so shaped as to fit conveniently into a control unit. The plan views varied as much as the front elevations, and were complicated by bulges and knobs which projected from the case. Mr. Hughes also suggested that the prepayment mechanism should be in the same place in all designs. Each maker had his own idea where the coin slot should be, and in many cases the insertion of the coin was awkward. He thought that the coin slot should be in the front of the meter, and that the complete prepayment meter case, including the coin box, should form a

clean rectangle—with the prepayment mechanism above the meter proper—that the terminal block should be at the bottom of the meter in exactly the same position as on a quarterly meter, in relation to the meter mechanism, and that the coin slot should be on the front of the case with the coin knob recessed. He believed that all this could be done without in any way retarding progress in design.

Although the main object of the meeting was to discuss meter design, the whole subject of the consumer's supply unit came under review. Decided views were expressed that units of the types designed and exhibited would not find favour in the ordinary house if they were to be placed in a prominent position for easy access, e.g. in the hall or sitting room. Suggestions were made that the units should be recessed in the walls in inconspicuous positions, although one unit of a more ornate character with a clock at the top and a looking glass occupying the remainder of the outside cover of the unit was regarded favourably by one speaker, who suggested the whole unit might be made to look like a grandfather's clock. On the whole, however, the suggestion that the units should occupy space in a hall or sitting-room did not meet with favour. Most speakers favoured locating the unit unobtrusively, at the same time making it easy of access. It was also thought that if an attempt were made to compress the various items of the unit into too small a compass, some limitation might be put on future development.

It was generally agreed that it was desirable to dispense with the prepayment meter altogether, though the time was perhaps not yet ripe for this.

Reports from large users all over the country showed a general agreement with the proposal to reduce the number of different meter ratings and to indicate clearly on the meter the maximum load at which it could be used, dispensing with the present short-range marking which, it was maintained, was largely disregarded. If this were done, it was claimed that a more efficient use would be made of the working range of a meter, which would automatically mean a reduction in the number of different ratings.

The need for measuring the consumer's load accurately was emphasized, but Mr. Hughes suggested in his reply that the word "economically" should be added here. He urged that the first step was to standardize the main dimensions of the meter case.

On the manufacturers' side, it was claimed that standardization should start with the user, i.e. with those who formulated the tariffs.

PROCEEDINGS OF THE MEASUREMENTS SECTION

115TH MEETING OF THE MEASUREMENTS SECTION, 19TH MAY, 1944

Mr. E. W. Moss, Chairman of the Section, took the chair a 5.30 p.m.

The minutes of the meeting held on the 21st April, 1944, were taken as read and were confirmed.

The Chairman announced the Council's award of Premiums (see Part I, June, 1944, page 208) for Measurements Section papers read or accepted for publication during the session 1943–44.

Dr. L. Hartshorn, Associate Member, then delivered his Lecture on "Foundations of Electrical Measurements."

A vote of thanks to the lecturer, proposed by Dr. W. G. Radley and seconded by Prof. L. G. A. Sims, D.Sc., Ph.D., was carried with acclamation.

116TH MEETING OF THE MEASUREMENTS SECTION, 14TH JUNE, 1944

Mr. E. W. Moss, Chairman of the Section, took the chair at 3.30 p.m.

The minutes of the meeting held on the 19th May, 1944, were taken as read and were confirmed.

The Chairman referred to the request made by several members of the Section that the Discussion opened on the 31st March last on "The Consumer's Supply Control Unit of the Future, and its Effect on the Design of the Electricity Meter" should be continued.

Mr. C. W. Hughes, B.Sc., and Mr. G. F. Shotter, Members, then made a brief recapitulation of the introductory remarks.

At the conclusion of the discussion a vote of thanks, moved by the Chairman, was accorded to Mr. Hughes and Mr. Shotter for their introductory remarks.

DEVELOPMENTS IN RAILWAY SIGNALLING ON LONDON TRANSPORT* ®

By R. DELL, Member.†

(*The paper was first received* 21*st May*, 1943, *and in revised form* 7*th January*, 1944. *It was read before the* MEASUREMENTS SECTION 17*th March*, 1944.)

(1) INTRODUCTION

The power-signalling installation on the railways of the London Passenger Transport Board now covers 160 miles of double track. There are 3 281 stop signals, 2 726 of which are fitted with trainstops. The number of track circuits is 4 347, and there are 1 326 pairs of points. Although automatic signals are used wherever possible, 112 signal cabins are in use at junctions or connections in the track layout. The passenger-train car-miles run each year on the Board's railways total approximately 159 150 000.

Power signalling has been in use practically throughout the system since it was electrified. The electrification of the District Line and the installation of power signalling commenced in 1904; by the end of the next year conversion had been completed and the block-telegraph type of signalling entirely replaced by power signals. The London Electric Tube Lines were from the start equipped with power signalling—the Bakerloo and the Piccadilly Lines in 1906 and the Hampstead Line in 1907. Two earlier Tube Lines, the City and South London Railway and the Central London Railway, retained their block-telegraph type of signalling for a few years, the Central London being converted to power signalling in 1913 and the City and South London in 1919.

Except for these last two installations, the whole of the signalling system was originally operated on d.c., and track circuits were of the d.c. type with polarized relays in order to avoid improper operation by stray current from the traction system.

In the original installation the signals were all electro-pneumatically operated with a moving spectacle in front of a fixed light for the tunnels and with semaphore arms in the open. All signals for passenger movements were provided with automatic trainstops. Although they gave remarkably satisfactory results, the d.c. track circuits were not entirely immune from interference by stray current from the traction system; as a result practically all these track circuits have been progressively replaced by a.c. equipment since the original system was installed. At the same time, many additional safeguards were added to the system. Alternating current is now employed throughout for all signalling circuits as well as for the track circuits themselves.

(2) ELECTRO-PNEUMATIC EQUIPMENT

Some of the basic features of the original signalling system, such as electro-pneumatic gear, have stood the test of time and have been retained in the more modern equipment. To permit direct comparisons under working conditions of the relative efficiencies of electro-pneumatic and all-electric gear, sections of signalling with all-electric equipment in place of the electro-

* Measurements Section paper.

† London Passenger Transport Board.

CHART OF SYMBOLS

SIGNAL Colour-light (controlled)	SIGNAL Colour-light (automatic)	SHUNT SIGNAL Disc type - with route indicator	SIGNAL LAMPS G Y R	INSULATED RAIL JOINT
RELAY AC (Two-element type)	RELAY AC (Single-element type)	RELAY AC (Time-element type)	RELAY AC N R (Point-control type) Two independent windings	POINTS AIR-VALVE MAGNET COIL
CONTACTS ON POINT-CONTROL RELAY N R CLOSED OPEN Shown with points normal	CONTACTS ON POINT-DETECTION RELAY N R CLOSED OPEN Shown with points normal	CLOSED RELAY CONTACTS OPEN Shown with relay energized	N R CONTACTS ON POINTS Closed when points are in appropriate position	ELECTRIC LOCK ON POINT LEVER
TRAINSTOP	DANGER ('ON') CLEAR ('OFF') CONTACTS ON TRAINSTOP Closed when trainstop is in appropriate postn	SHUNT SIGNAL	DANGER ('ON') CLEAR ('OFF') CONTACTS ON SHUNT SIGNAL Closed when signal is in appropriate position	40 SPEED-RESTRICTION SIGN
ELECTRIC GROUND LOCK ON POINTS	Shown in normal position POINTS On plan On diagram	Shown in normal postn TRAP POINTS On plan On diagram	N LOCKING FRAME LEVER CONTACT Closed when lever fully normal	R LOCKING FRAME LEVER CONTACT Closed when lever fully reversed
NC LOCKING FRAME LEVER CONTACT Closed from normal to midstroke position	RC LOCKING FRAME LEVER CONTACT Closed from reverse to midstroke position	AE LOCKING FRAME LEVER CONTACT Closed during whole of lever stroke except full normal & full reverse positions	H LOCKING FRAME LEVER CONTACT ON PUSH-PULL FRAME Closed when lever fully in "PUSH" position	LM LOCKING FRAME LEVER CONTACT ON PUSH-PULL FRAME Closed from "PULL" position to normal (MID) position

pneumatic type have been installed and the performance carefully watched. The simplicity of the electro-pneumatic apparatus, which requires only a simple cylinder and piston to furnish all the force necessary to operate a trainstop arm or a pair of points, has proved a great advantage; the maintenance required is considerably less than for electric gear, whilst the lighter weight of the equipment enables it to be more easily serviced when worn or defective pieces need replacing. In addition, the electro-pneumatic equipment is more reliable than the all-electric. Fig. 1 shows a modern electro-pneumatic trainstop designed for use in tube tunnels.

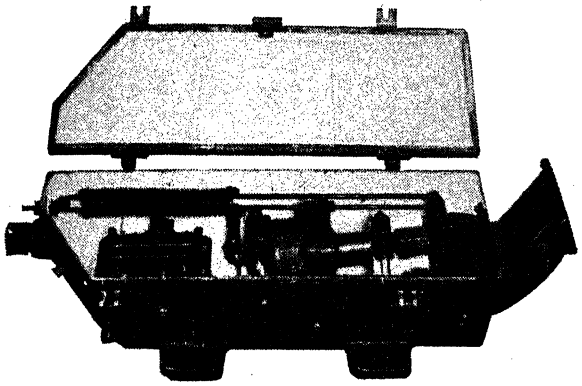


Fig. 1.—Electro-pneumatic trainstop for Tube tunnel fixing.

(3) SYSTEM OF SIGNALLING ASPECTS

The signalling problem on the Board's railways, which handle passenger traffic only, is simpler than that of other railways, and the main task of the signal engineer is to make provision for the safe running of the maximum number of trains under set conditions. To meet these conditions, two-aspect signals are considered to give the best results possible, since only two instructions to the driver are necessary, whether to proceed or to stop. The greatest number of trains can be run over any section of the line if the driver follows just these two instructions —when he observes a green signal he proceeds as fast as he can, in accordance with any permanent-way speed restrictions, and when he sees a red signal he stops at it as quickly as he can.

It has been found advantageous to adopt this principle in every possible case, and recently special steps have been taken in certain tube tunnels to ensure that a driver does not see a red light unnecessarily—in other words, the red light is controlled by the track circuit so as to remain extinguished until the driver is so close to the signal that he has to apply his brakes in order to stop when he reaches it. This arrangement frequently saves the driver wasting time, for in the absence of landmarks in a Tube tunnel a red light in the distance may appear closer than it really is, with the result that the driver slows up before he need do so; often the signal will change to "clear" long before the train gets close to it, so that, had the driver not slowed up, the signal would still have cleared before he reached it.

Recent new installations of two-aspect signalling have been of a modified type, one signal only at each location being provided for each line. The signals are two-aspect, showing red and green lights, but repeaters are provided where necessary. For example, where the curvature of the line would prevent a driver seeing a red light in time, a repeater is provided just round the curve. The repeater shows green when repeating the green light of the signal, and yellow when repeating the red light of the signal.

When there are divergent routes, a junction indicator comprising a series of white lights which can be exhibited at various angles is provided. The light of this junction indicator, together with the light of the signal, indicates to the driver whether it is safe to proceed and in which direction he is going. Thus, if the signal is showing clear and the junction indicator shows a row of lights above the signal at an angle of 45° to the left, the driver knows that he is to proceed over the first route to the left of the main line. If the signal shows clear with the junction indicator lamps forming a horizontal line to the right of the signal lamp, the driver knows that he is to proceed over the second route to the right, counting from the main line. Fig. 2 shows a colour-light signal with junction indicator.

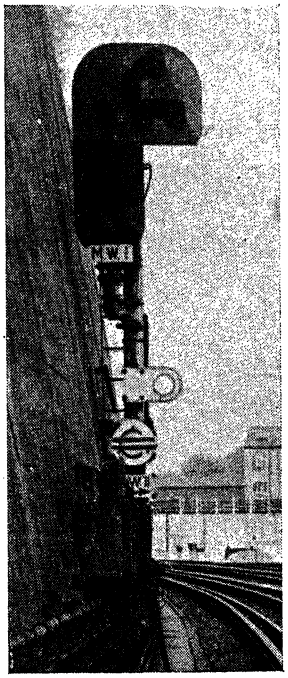


Fig. 2.—Two-aspect colour light signal with junction indicator.

All subsidiary or shunting movements—which are signalled movements for empty trains to proceed to sidings or to couple up or uncouple—are regulated by disc signals comprising a white-enamelled iron disc with a red band on it. With the red band in a horizontal position the signal is at danger; by rotating the disc the band is turned to an angle of 45° to indicate "proceed." Where the shunt signal is required to read into a series of sidings, for example, a route indicator is provided above it showing an illuminated figure and indicating to the driver the route which has been set up for him. Thus, if a shunt-signal disc is showing "proceed" and exhibiting the

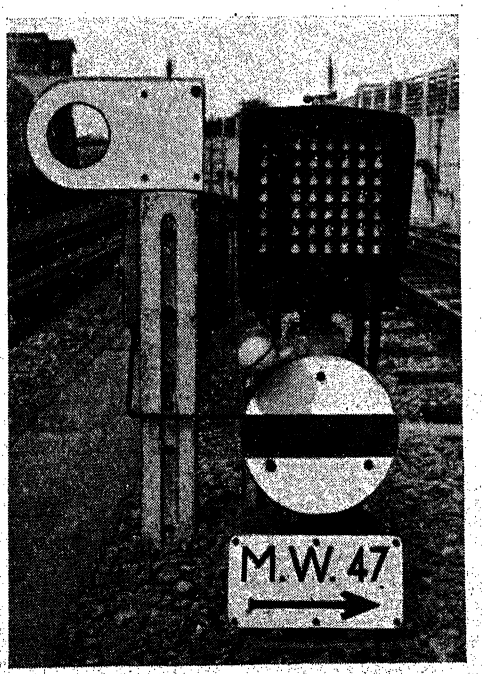


Fig. 3.—Disc signal with route indicator.

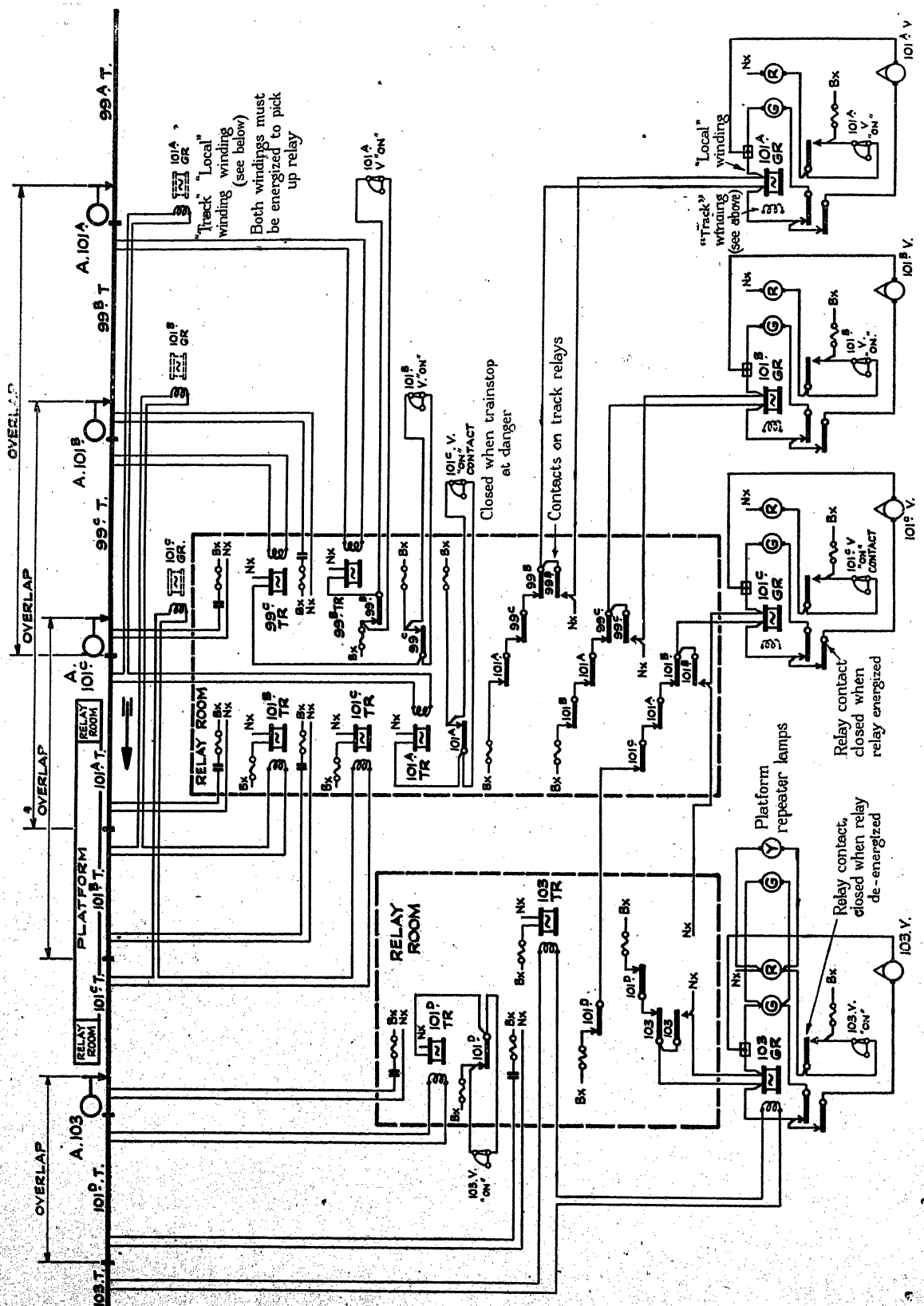


Fig. 4.—Automatic signalling circuits.

A = Automatic signal.
G = Signal.
GR = Signal relay (two-winding type).
T = Track circuit.
TR = Track relay (two-winding type).
V = Trainstop.
BX = A.C. supply, feed.
NX = A.C. supply, return.

figure "3" on the route indicator above it, the driver knows that he is to proceed for a limited distance into a siding and that he is taking the third route from the left. Fig. 3 shows a disc signal with route indicator.

With this system of signalling the confusion likely to arise with a large bridge of signals, as provided in earlier installations, is avoided; at the same time, the driver is not called upon to pass a red light when proceeding on a main-line passenger movement. He does, of course, pass a red light when proceeding under control of a disc signal, but this appears to the author to be an advantage, as it draws attention to the restricted nature of the movement to be made by the driver.

(4) TYPICAL AUTOMATIC SIGNALLING IN TUBE TUNNELS

Fig. 4 shows the signalling circuits at a Tube station equipped with the most modern a.c. signalling gear. The signals shown are three home signals and a starting signal. Arrangements have been made for the bulk of the electrical apparatus to be installed in relay rooms built at the ends of the station platforms, so that only the signal lamps together with their controlling relay, and the trainstops with their connecting cables, are actually in the tunnel. This has been done to facilitate attention to the equipment during traffic hours, as owing to the smallness of the tunnels, staff cannot enter them whilst trains are running.

A special feature that should be noted is that each of the most important track circuits, namely, the berth track-circuit, is provided with two track relays, the track windings of these relays being connected in series. One of the relays functions as a track relay proper, whilst the other, by switching its local winding over the appropriate contacts, functions as a signal relay. The purpose of this arrangement is to introduce an additional safeguard against any accident resulting from failure of one relay to operate correctly, since both relays must be energized for the signal to show clear.

The track windings of two such relays are shown at $101^{B}TR$ and $101^{B}GR$. $101^{B}GR$ serves as a signal relay for $A.101^{B}$; the connections to the local winding are shown at $101^{B}GQ$.

It will be noted that the circuit to the red light of the signal is completed by two independent contacts, one on the relay and one operated by the trainstop. This ensures continuity of current supply to the red light, should either of the two contacts become defective. It also serves as a valuable indication to the driver that the trainstop is working correctly, for should the trainstop fail to operate when the signal clears, the red light will not go out and the driver will see both red and green lights in the signal, thus disclosing the fault to him.

Trainstops are provided with proving circuits to ensure that they operate correctly for the passage of each train. Such a proving circuit is shown operated by the trainstop contact $101^{B}V$, and is so arranged that 99^{C} track relay cannot clear following the passage of a train until 101^{B} trainstop has returned fully to danger. This, in turn, would prevent the previous signal 101^{A} from clearing.

(5) ADVANTAGES OF THE FOURTH-RAIL TRACTION SYSTEM

The traction system on the Board's railways employs a fourth rail for the return of the traction current, the system not being directly connected to earth except through the general leakage of the system. This arrangement offers definite advantages from the signalling point of view. Although the third-rail system can be adopted and is in use elsewhere, signalling arrangements are made more difficult.

With the fourth-rail system one continuous running rail is necessary to provide an earth for the framework of the train, whilst the other running rail can be split up by insulated joints for the track circuits. Examples have been known where insulated rail-joints have been put in both running rails with a fourth-rail traction system, but this is most inadvisable, as in the event of an electrical defect occurring on a train, any person stepping on to the train or touching the metalwork could under such conditions receive a serious shock.

It appears at first sight that the employment of a fourth rail for the traction return is extravagant, as compared with the use of the running rail for the dual purpose of a return and for signalling. In fact, careful calculations have shown that when allowance is made for a frequent service of trains, the additional cost of the signalling is more than the saving made on the fourth rail. The losses are also less with the fourth-rail system, as the comparatively hard rails used for running have a higher resistivity than the soft steel usually employed for current rails. With the third-rail system the return path for the traction current, after the rails have been divided into sections for signalling, has to be provided by impedance bonds, which are centre-tapped choke coils capable of carrying the whole of the return traction current. It is the cost of providing these impedance bonds which increases the cost of the signalling installation over that required with the fourth-rail system.

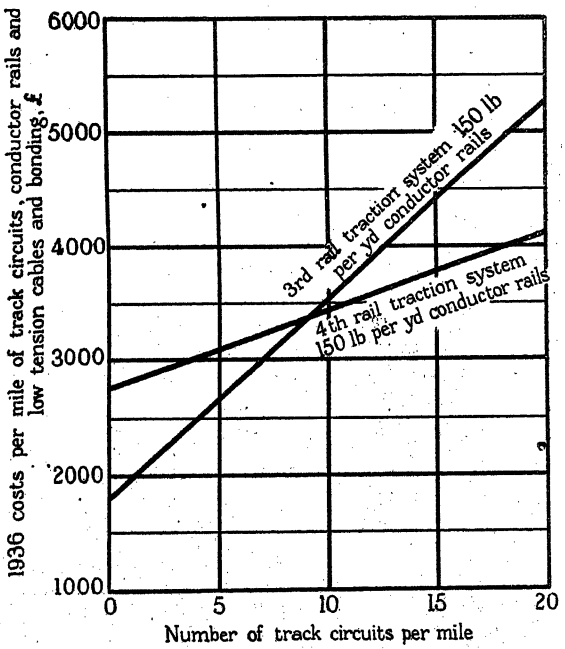


Fig. 5.—Relative costs of third and fourth rail traction systems, including cost of track circuits.

The curve in Fig. 5 shows the cost of a signalling installation on the basis of prices ruling in 1936, indicating the rise in cost of the third-rail type of signalling with the number of track circuits per mile as compared with the cost of fourth-rail signalling and the cost of the fourth rail. Apart from the question of cost, the signalling system feasible with fourth-rail traction is very much simpler in design, less susceptible to maladjustment and easier to operate.

It may be mentioned that the average number of track circuits per mile on the Board's lines is 18.

(6) CONDENSER-FEED TRACK CIRCUIT

With the introduction of the a.c. track circuit in place of the original d.c. track circuits, various systems of regulating the current feed to the track circuit were tried. Plain resistance

control, choke control and various other types were used for a time, but considerable trouble was experienced owing to temporary failure of the track circuits, arising from stray current from the 600-V d.c. traction system, and in 1922 the condenser-feed track circuit without a transformer between the condenser and the track circuit was introduced. Since that time, this type of track-circuit feed has been standardized throughout the Board's system and has proved extremely satisfactory in operation. The arrangement of the track circuit is shown in Fig. 6.

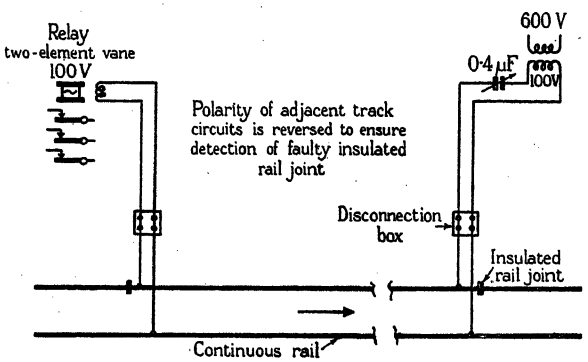


Fig. 6.—A.C. track circuits, condenser-feed type.

The provision of the condenser in this circuit blocks the passage of d.c., which would otherwise cause saturation of the iron of the feed transformer or of the relay, with a consequent interference with the operation of the track circuit. The condenser has a number of tappings connection to which is made by links attached to the terminals; and a great advantage of the circuit is the ease of adjustment, there being only the simple adjustment of increasing or decreasing the capacitance of the circuit.

With this type of track feed and the relatively high voltage employed on the track relays, the train-shunt conditions obtained are consistently good. An average value for the train shunt is approximately 2 ohms.

SOME TYPICAL VALUES OF TRAIN SHUNT TOGETHER WITH OTHER OPERATING VALUES TAKEN FROM ACTUAL TRACK CIRCUITS

Length	Position of section	Train shunt	Relay voltage	Feed-end voltage	Condenser capacitance
		ohms	V	V	μF
911 ft	Open	1·7	5·4	5·5	30
515 ft	Open	1·9	5·3	5·4	29
294 ft	Open	4·5	4·4	4·5	18
797 ft	Tunnel	4·0	4·0	4·8	15

(7) RAIL CIRCUITS

In operating the signalling system it is sometimes necessary to detect the exact position of a train. For example, before a calling-on signal is cleared, it must be established whether the train has come to a stand, or practically so, at the signal. Hitherto various types of treadles have been used for this indication, but all were troublesome to maintain and were liable to frequent failure. A special circuit, normally de-energized, was therefore developed; it is interposed in the usual track circuit and arranged so as not to interfere with the correct operation of the track circuit.

A rail 11ft 6in long is insulated from the rest of the track circuit and bonded round. This length is the shortest that could be approved by the Permanent Way Engineer, but is sufficiently short to ensure that no vehicle can stand on it without also standing on the track circuit. A standard a.c. track relay is connected to the rail section and to a supply of current through step-down and step-up transformers; the circuit is shown in Fig. 7. The ratio of the transformers is so adjusted that the

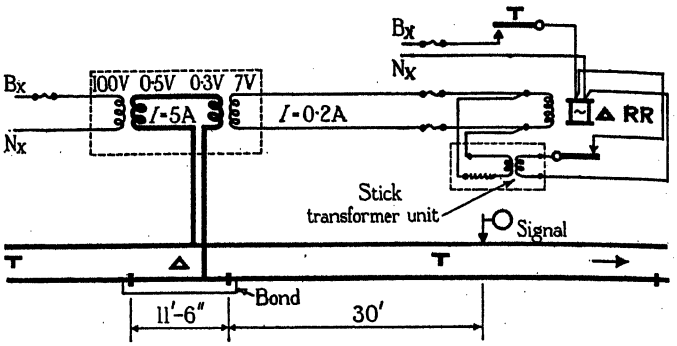


Fig. 7.—Rail circuit.

BX = A.C. supply, feed. NX = A.C. supply, return. T = Track circuit.

voltage on the rail section does not exceed 0·5 volt, whilst the current required to operate the relay is comparatively heavy, about 5 amp, the impedance of the circuit being low. This arrangement ensures that, even if the insulation of the insulated joints should break down, there can be no risk of improper operation of either of the circuits by leakage of current from the other. The voltage of the rail circuit is too low to operate the relay of the track circuit, and the current passed by the condenser of the track circuit is much too small to operate the rail circuit. Owing to the low voltage and high current of the rail circuit, the impedance of the rails prevents the operation of the circuit until the wheels of the train are within a few feet of the connection to the special rail section.

A "stick" circuit is provided to hold the relay of the rail circuit once it has been operated by a train. This is also shown in Fig. 7; it comprises a feed from the local winding of the relay through its own contacts, and has a small step-down transformer with a resistance incorporated for phase correction. This "stick" circuit holds the relay in the energized position, whilst the train is standing on the track circuit, once the rail circuit has been operated; in this way erratic movement of the relay is prevented whilst the train is running over the rail circuit.

(8) RELAYS

With the introduction of a.c. supplies for signalling, relays of an entirely different type from those used in the earlier d.c. installations were adopted. A signalling relay for use on a.c. must be absolutely reliable in operation and must not be operable by d.c. The need for reliability is particularly important when the relay is de-energized, as in no circumstances must the relay contacts then fail to open.

After some earlier installations employing single-element vane relays and galvanometer relays, the two-element vane relay was adopted early in 1920 for use on track circuits and for point indication in the Board's signalling system. After the original two-element vane relays had been in use some seven or eight years, careful investigation was made into their design and improvements were introduced which led to the relay used at present.

(8.1) Operating Characteristics of Two-Element Vane Relay

In a relay for use on railway track circuits a considerable variation in the amount of current available for the energization of the relay occurs between wet and dry weather, and on the earlier types of two-element vane relays the normal current was sufficient to compress the contact springs and such over-energi-

zation as occurred in dry weather merely caused the movement of the relay to hammer against its stop, which tended to damage the pivots. It was therefore decided to modify the arrangement of the contact springs, so that with greater energization the contact pressure would be increased and most of the added force expended in additional contact pressure. Furthermore, a modification in the shape of the relay vane gives a characteristic whereby the relay torque is considerably decreased as the edge of the vane moves out of the flux. In consequence, a considerable increase in current in the operating coils does not produce a proportional increase in the pressure on the contacts and, as a result, increased mechanical strain upon the relay movement.

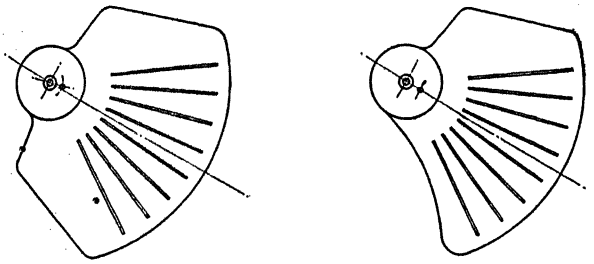


Fig. 8.—Two-element vane relay.

Fig. 8 shows the original and modified shapes of vane, while Fig. 9 shows the torque characteristics of the relay movement throughout its travel, with the modified shape of vane, and the force necessary to operate the contacts. The torque curves represent values at various voltages applied to the relay track windings. The points of intersection with the contact-force curve show the position at which the movement stops for various

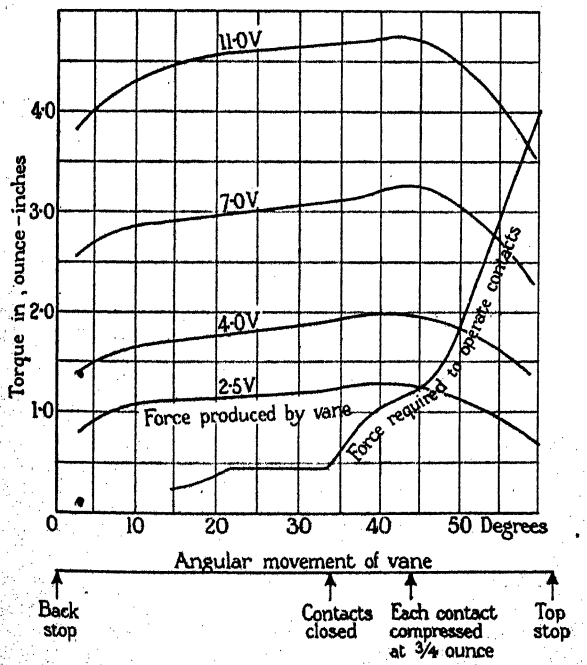


Fig. 9.—Two-element vane relay. Torque curves of improved vane.

applied voltages. It is seen that a considerable degree of over-energization can be applied without the vane pressing on the top stop. The higher values correspond to the working of the track circuit during dry weather, and the lowest curve shows the minimum value that should be permitted during wet weather.

As mentioned above, an essential feature of a signalling relay is that there must be absolute certainty that the contacts will open when the relay coils are de-energized, and to ensure this condition it is considered essential for one of each pair of contacts to be of carbon. Apart from selecting different grades of carbon, this does not leave much scope for variation in the contacts. Although other materials have been tried, so far silver-to-carbon contacts have given the best results.

With the early types of relay, a contact pressure of $\frac{3}{4}$ oz was provided under working conditions, but an investigation of contact failures indicated that somewhat higher contact pressures would reduce the number of failures. Track feeds are now generally adjusted to ensure that the contact pressure falls below 1 oz only under the most severe conditions, while remaining stable around $1\frac{1}{4}$ oz under the normal working conditions. This has resulted in a very considerable reduction in contact failures.

(8.2) Twin-Vane Relay

Upon the reliability in operation of the track relay depends the whole safety of the signalling system, and, whilst extraordinarily reliable results have been achieved with the present types of relays, it has nevertheless been felt that further improvement in this direction is desirable.

A design has been worked out for a track relay containing a twin-vane movement in which two separate vanes actuate two separate sets of contacts, the two vanes being operated by the same magnetic circuit and the two corresponding contacts of each half of the unit being connected in series. The two vanes are mechanically interconnected, so that as long as they continue to function exactly together, the operation is normal; but should one of the vanes lag behind the other, owing to the pivots sticking or some other mechanical binding action supervening, the mechanical coupling will lock the opposite movement and put the relay out of service, thus automatically bringing to light any defect which might develop and cause a dangerous condition.

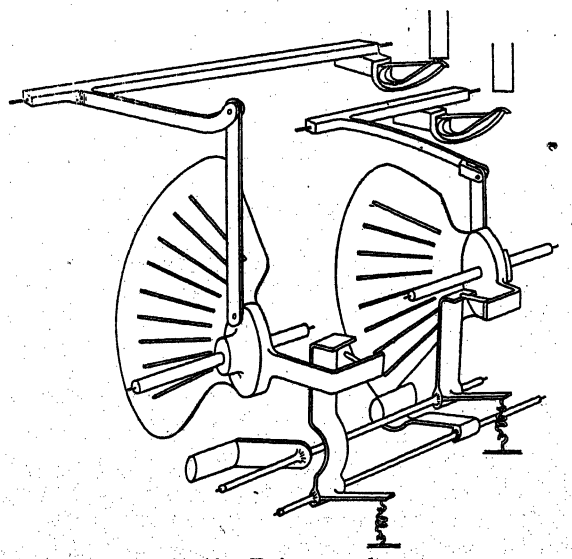


Fig. 10.—Twin-vane relay.

Fig. 10 shows diagrammatically the operation of the twin-vane relay.

The development of this new relay has not yet progressed beyond the stage where a single experimental relay has been built.

(8.3) Point-Control Relay

When the introduction of remote-control signalling was contemplated, a further relay was considered necessary to

ensure the safe and satisfactory working of point circuits. The special point-control relay designed for this purpose has a single-vane movement carrying two sets of contacts so arranged that the contacts are held closed by gravity in whichever of its two positions the relay is left.

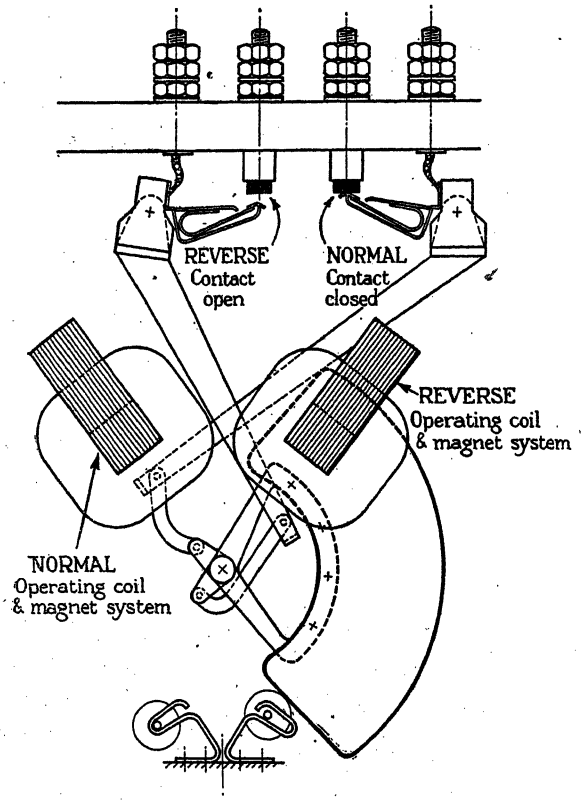


Fig. 11.—Point-control relay.

Fig. 11 shows the arrangement of this relay, in which the two magnetic systems with energizing coils tend to drive the vane in opposite directions. Whichever movement the vane is making, it is lifted over dead-centre and falls by gravity, aided by the power drive of the magnetic system, into one direction or the other, thus closing one set of contacts and opening the other set.

This relay is mainly used to maintain current on the point-operating mechanism when the points have been set and the automatic-control circuits have been interrupted by some alteration in the circuit conditions. The special feature of this relay—that the contacts are maintained closed at the full contact pressure, whether there is current on the relay or not—has been of great help in designing relay-interlocking circuits.

(8.4) Standardized Relay Frames and Detachable Terminal Tops

About 1928, the detachable terminal top was introduced in the a.c. relay and has become a standard fitting for all the Board's relays. As a result, although different types of relays have been adopted from time to time, the same case and standard detachable terminal top have been retained, thus giving a marked standardization of fittings.

(9) ELECTRIC AND COMPRESSED-AIR SUPPLY

Some care was found necessary in arranging the main supplies for the signalling system to ensure continuity of service and also to provide that in the rare event of a breakdown any supply could be restored as quickly as possible.

In recent years it has become the practice on all the more important sections of the Board's lines to provide a separate main-current supply and compressed-air supply on each side of a double line of track, feeding the signalling for the northbound road from one source and that for the southbound road from the other source.

(9.1) Electric Supply

Fig. 12 shows the arrangement of the electric supply for the signalling system. The supply is fed from the Board's own

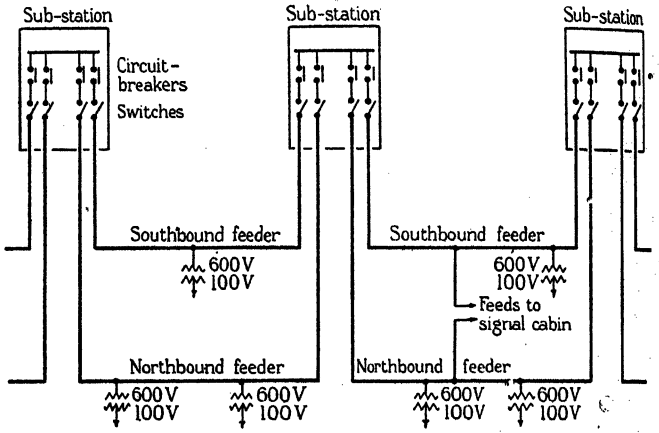


Fig. 12.—Signal main feeding arrangements.

substations, and 600 volts is employed for the main supply. Armoured cable is used where the cable is installed in the open, being supported in cast-iron brackets on concrete cable-posts or on walls, as required. At each point where a tapping is required, a transformer is provided and links are connected to the supply cable, so that every tap becomes a point at which the supply can be isolated. The transformers have three secondaries providing connections for two track circuits and one secondary for the signal circuits. In the event of a fault developing on the main cable, the faulty section can be isolated by means of the links and all signal equipment left in operation.

In the signalling circuits, and particularly in the point-indication circuit, polarized a.c. relays are employed; this requires a safeguard against a reversal of phase between one part of the main system feeding the polarized circuits and any other part, as a result of switching at the feed point. For this purpose, arrangements are made at point connections for the main cable to loop as far as the limit of the connections involving point

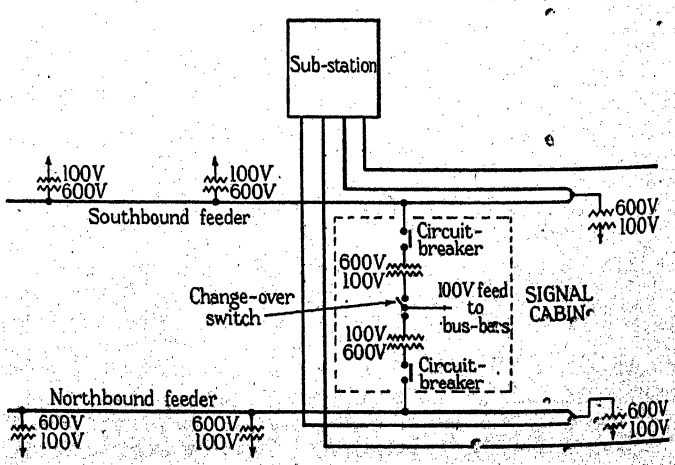


Fig. 13.—Signal main feeding arrangements. Looped feeders at signal cabin adjacent to substation.

indications, thus ensuring that all such circuits are fed from the same source. This arrangement is shown in Fig. 13.

(9.2) Advantage of Special Frequency

The Board supply current from their own power stations at a frequency of 33⅓ c/s; from a signalling point of view this is extremely valuable, as other supplies are at 50 c/s. Stray current from a.c. circuits passing through earth are liable to create a potential difference between two earthed points, and should this occur in the vicinity of a railway, track circuits operating from the same frequency might be improperly actuated. By having a frequency different from the usual commercial frequency, this risk is avoided.

It might be mentioned that leakage currents from 50-c/s supply circuits have been detected. In one case arches under the railway had been let to traders who installed lighting attached to the brickwork. A faulty circuit in this lighting system gave a leakage current of such a value that a potential difference of several volts could be measured between two test rods inserted in the ballast of the railway above. This leakage current entered the track circuits, but owing to the difference in frequency fortunately caused no improper operation.

(9.3) Compressed-Air Supply

A supply of compressed air is required for operating electro-pneumatic signalling gear. In the Board's system, compressors are installed at all substations and provide a constant supply of compressed air to the main air pipe run throughout the system. As in the electric supply system, the general practice is now to duplicate the compressed-air supply pipes. These pipes at the same time afford a convenient support for the signalling cables.

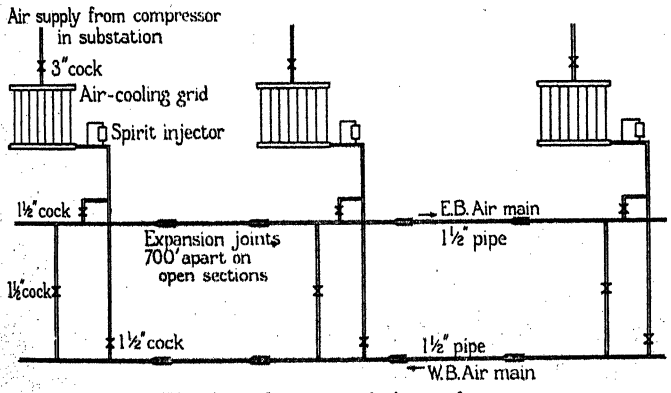


Fig. 14.—Compressed-air supply.

Fig. 14 shows the arrangement of the supply pipes with feeder pipes feeding into the main supply at each substation. Before entering the main supply pipe, the compressed air from the compressor is passed through cooling grids to extract moisture. Isolating cocks are provided in the main supply wherever a tapping is taken from the main, to permit isolation, should a leak develop.

The compressed-air system has proved one of the most reliable parts of the signalling installation, and failures from a burst pipe or other causes have been extremely rare.

(10) CABLE RUNS

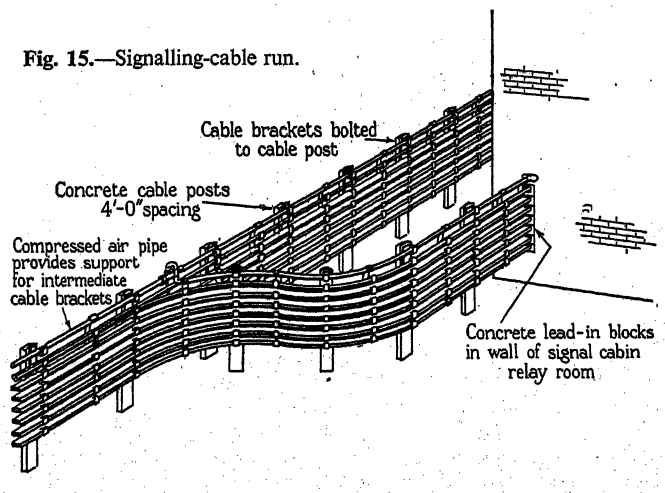
In the original installation, much of the cable required for signalling was installed underground in cable ducts. Faults soon developed in the cables, and as a result entirely different arrangements had to be provided for the support of the signalling cables. At the same time the design of the cable runs has also been carefully studied.

Unless care is taken in the installation and arrangement of the cables, there is always the danger that stray current from the 600-volt traction system may cause burning of the lead sheaths, with consequent failure of the cables or even a fire destroying them. Lead-sheathed cables are employed throughout, and, mainly by suitable arrangement of the cable runs, special precautions are taken to protect them against damage from stray currents.

In particular, care must be taken that the lead sheaths do not come into contact with any earthed objects, such as a water pipe, a bridge girder, a station stanchion, etc. At the same time, the lead sheath must be earthed; and a practicable method has been found in the provision of cast-iron brackets supported on concrete posts or on walls for making an earth connection for the lead sheaths in the form of a distributed leak of such a value that a low resistance reading is obtained at any point between the lead sheath and earth. There is no particular path forming a low-resistance earth connection. The lead sheaths are never bonded to earth plates, etc., but are bonded together to form a continuous system throughout the railway. In effect, the signalling installation thus has its own private earth system provided by the lead sheaths of the signalling cable; this system is earthy throughout but not earthed at any particular point.

The arrangement of the cable brackets has been modified from time to time. In early installations, a spacing of 4 ft between brackets was common, but this was found too wide for small signal cables and a fracture of the lead sheath resulted. A bracket spacing of 2ft centres has been adopted in all recent installations. The compressed-air supply main, which is placed at the top, forms a convenient support for intermediate brackets to provide this close spacing. Fig. 15 shows the arrangement of a typical cable run and its connection to the signal-relay room.

Fig. 15.—Signalling-cable run.



In the earlier designs of cable brackets, convenient dimensions were chosen to hold a reasonable number of cables, without any reference to the actual size of the cables. This resulted in a somewhat untidy array of cables, and injury to the lead sheaths often occurred where one cable crossed another. Cable brackets are now designed to accommodate the exact number of signalling cables, these being laid in straight lines in layers. This gives a much neater installation and improves the life of the cables. A cross-section of the bracket run is shown in Fig. 16.

It is inevitable that at some points the signal cables be taken across the railway tracks; maintenance at these points has always proved very difficult. Underground ducts were found unsatisfactory, and concrete troughs with detachable lids, laid on the surface, have been designed where small runs of cable only are required. These troughs permit the cables to be laid-in one

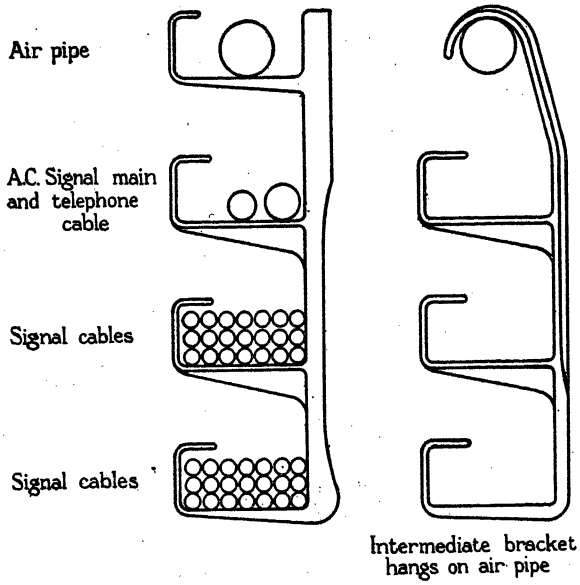


Fig. 16.—Cable brackets.

by one without injury, while the lids can be removed periodically for inspection of the cables. This feature also permits the renewal of a defective cable without injury to the others.

Where a large number of cables must be taken across the track, the provision of a cable bridge is the only satisfactory solution so far found. In the Board's installations carried out in the last twelve years, many bridges have been erected for the sole purpose of carrying cables over the lines. Considerable care is necessary in the design of the cable supports on these bridges, and special provision must be made for adequate support where the cables turn on entering and leaving the bridges.

(11) CABLING OF SIGNAL CIRCUITS

With very few exceptions, the signalling cables employed on the Board's system have always been lead covered and rubber insulated. On the original installation some circuit portions consisted of multi-core cables. For example, 4-core cable was used for the control and indication of signals and 6-core cable for the operation and indication of a pair of points. Although these multi-core cables were retained as individual to each signal or points, and in all cases the incoming track-control lines were run in separate cables, difficulty with breakdown of the insulation of the multi-core cables was experienced quite early, and it was found that when this occurred dangerous conditions could be set up.

Certain limited installations were provided with more extensive multi-core cable systems, and in these not only would a multi-core cable feed one individual signal or pair of points, but the control for several signals, pairs of points, or even incoming lines from track circuits, would be included in the same cable.

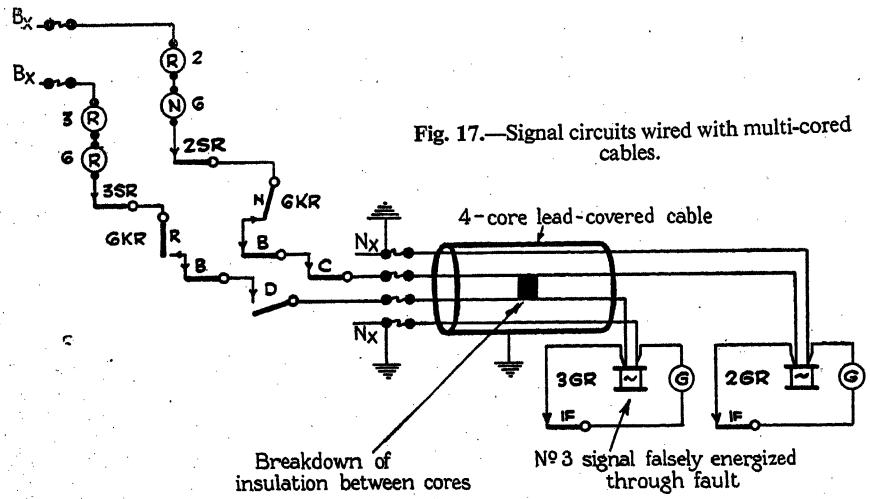


Fig. 17.—Signal circuits wired with multi-cored cables.

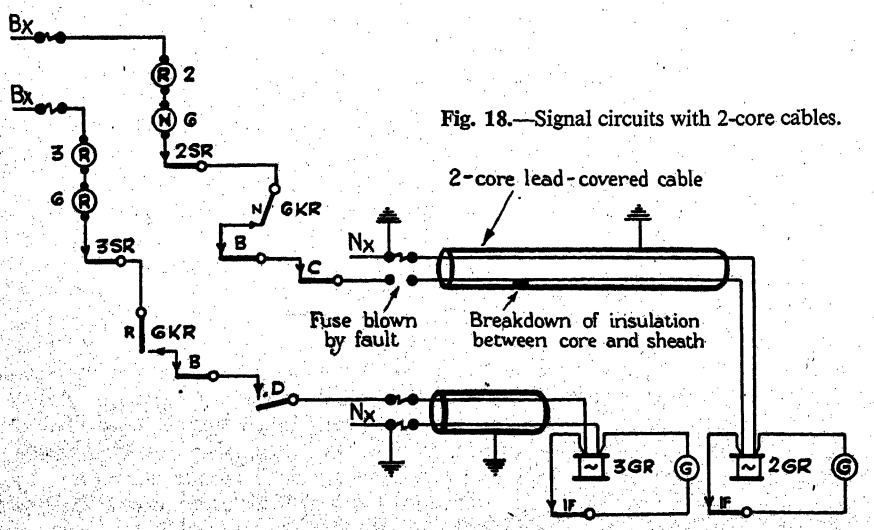


Fig. 18.—Signal circuits with 2-core cables.

It will be readily appreciated that where a number of circuits are included in a multi-core cable without an earth screen between the individual conductors, a breakdown of insulation can very easily cause false operation of a circuit by current from a live circuit passing through the faulty insulation on to a circuit which should be dead. It might be suggested that constant testing of the insulation of the cables would prevent ill effects, but the author believes that such tests cannot be relied upon for absolute safety as he has known cases where a cable with faulty insulation gave quite good insulation readings dry, whereas, after wetting, the same cable gave extremely bad readings.

Arising out of the experience gained with these earlier installations, all the Board's later signalling installations have employed individual 2-core cables for all circuits. With this system no cable contains more than two cores, which are employed for the feed and return of one circuit only. The cable has a lead sheathing which provides an earth screen between the live circuit and any other circuit which could be connected through another cable. With this system the lead sheaths are all connected to the NX side of the transformers, and immediately a fault develops in any insulation on a live circuit a direct connection between BX and NX occurs, the fuse is blown and the dangerous condition is avoided.

Fig. 17 shows circuits connected through a multi-core cable and how a fault in the cable can cause current to leak from one circuit to another, thus giving a false opera-

tion. Fig. 18 shows similar circuits with individual lead-covered cables, where the lead sheath is seen effectively to screen the live circuits from each other.

The use of multi-core cables has the one advantage of cheapness, as so many circuits can be enclosed in the same lead sheath, making a cable cheaper in first cost, as well as giving some saving in the cost of cable runs and the cost of laying the cable.

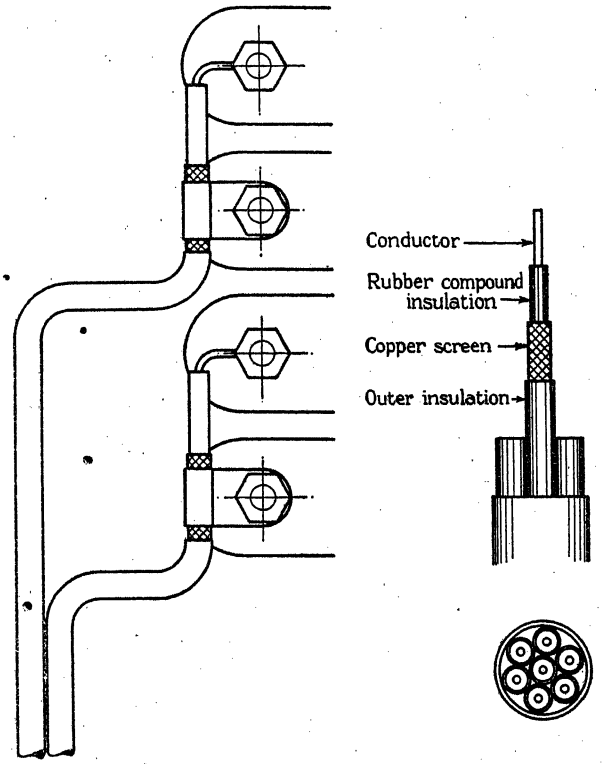


Fig. 19.—Suggested cored cable for railway-signalling purposes.

The use of individual lead-covered cables is not the only way of providing screening between circuits, and when the time is more suitable for development it may be possible to produce a multi-core cable with efficient inter-circuit screening, thus meeting a vital safety requirement in signalling. The advantage of reduced cost offered by the multi-core cable might then be combined with the safety afforded by the screened system.

Fig. 19 is a suggested design for such a screened multi-core cable for signalling purposes. The screen consists of either copper braid or a very thin copper tube, and could also form the normal return for the signalling circuit so that each core of the multi-core cable with its outer screen would provide a complete circuit. Each screen could be provided on the outside with a thin layer of insulation, thus enabling circuits to be tested individually, including the return, and ensuring continuity of the direct return, with an earth connection at the feed point only.

(12) EARTHING OF SIGNALLING CIRCUITS

The original d.c. circuits used for signalling employed an earthed return, the running rail being used as the return circuit for all signalling current.

When a.c. signalling was first introduced, an all-insulated system was adopted, but it was soon realized that with this system two earth faults could give a false operation. Consequently, a system of continuous earth detection was provided at signal cabins having extensive circuits fed from the same transformer. Long experience with this deteetor system on many installations over a number of years and further careful consideration led to the decision to abolish earth detectors and to revert to the earthed system. This is the arrangement now adopted on all signalling circuits; in the opinion of the author, it is the safest possible arrangement and far superior to any all-insulated system employing earth detectors. Provided that care is taken to ensure the continuity of the earth connections, the system is absolutely safe and affords protection against any possible false feed through leaky insulation.

The earth connection is made between the NX of the transformer secondary and the lead sheathing of the cables. Special care is taken in making these connections; they are soldered direct to the busbars, duplicate cables being run to the top and the bottom of the busbars. Although it might have been better to make a solid soldered connection from the busbar to the lead sheath, provision for removing the connection for periodical testing of the insulation of the whole system was considered desirable. For this reason, the final connection to the lead sheaths is carried out by means of strips of copper soldered to the sheaths and fixed by means of bolt-and-nut terminals; three separate strips of copper under three separate terminals are provided to guard against a loose connection on one or two of the terminals.

Fig. 20 shows the earthing arrangements in a signal-cabin relay room.

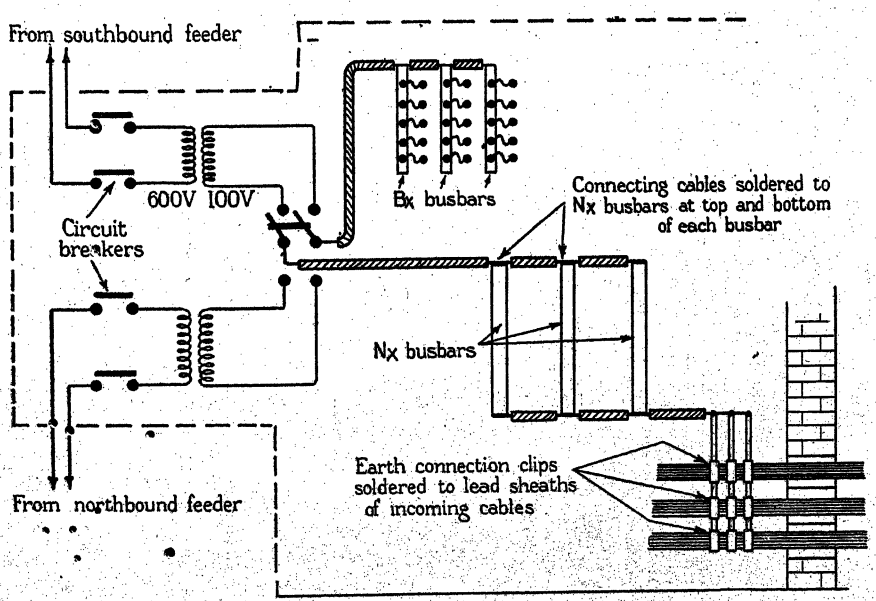


Fig. 20.—Earthing arrangements at signal cabins.

(13) DESIGN OF SIGNAL CABINS AND RELAY ROOMS

In the earlier types of signal cabins much wood was used for the structure and fittings. Wooden relay racks or cabinets were fitted and the wiring was cased in wooden trunking. Often large wooden troughs containing hundreds of wires were built into the floor of the signal cabin or relay room. Trouble was sometimes experienced from mice or rats getting into the wire runs and damaging the insulation, and the whole construction involved a serious risk from fire.

The design of signal cabins and relay

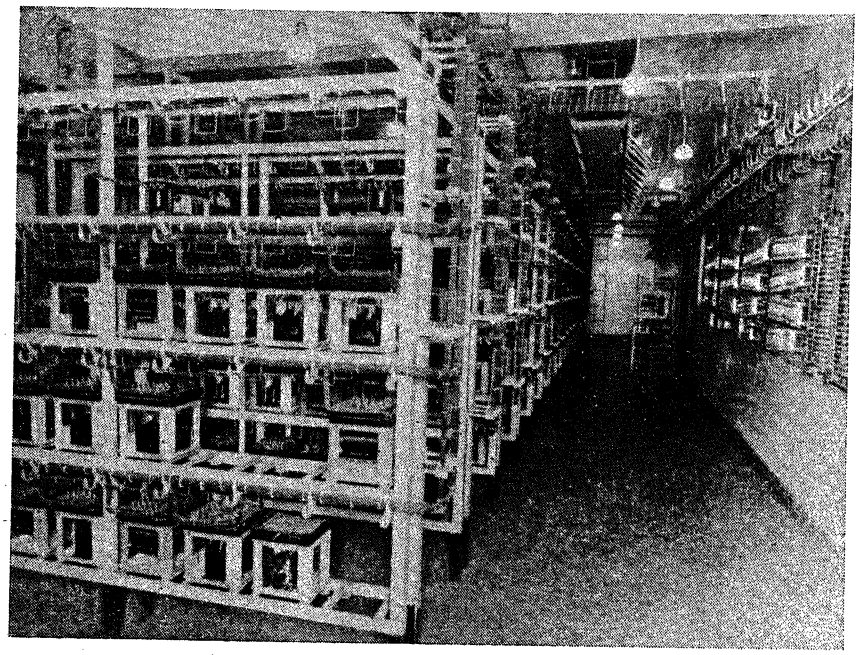


Fig. 21.—Signal-cabin relay room, showing relay racks and wiring, also ladder access to underside of locking frame.

rooms adopted during the last twelve years endeavours to meet the following requirements:—

(1) Fireproof construction
(2) Freedom from trouble caused by mice or rats
(3) Accessibility of all equipment for easy maintenance without need to remove covers
(4) Clean and comfortable accommodation for the signalman

The buildings are designed to suit the surrounding conditions, special consideration being given to the arrangement of cable entries, which are located well above the floor level. By the provision of entries at several points a congestion of cables at one point is avoided.

Relay racks are of steel and are arranged to be clear of the walls of the relay room so as to give full access to both sides of the relays and to the wiring. The racks are of skeleton construction, thus providing the minimum area for the accumulation of dust. They are built of standardized components from which racks of any required size can be readily assembled. The wiring supports are arranged with the hooks in tiers at an angle of 45° on the horizontal runs, so that wires can turn out at any point required without having to cross adjacent runs.

Direct access to the underside of the interlocking frame is provided from the relay room, giving a direct way for the wiring, which is carried up in a series of small runs, avoiding large bunches of wires and giving ready accessibility.

Fuses are provided at all points where incoming or outgoing cables terminate inside the relay room, thus giving a convenient testing point. The fuses are mounted on the walls of the relay room and are fitted on strips of channel steel slightly inclined, so that the minimum wall space is occupied by incoming and outgoing cables. Busbars are provided for the feed and return of circuits, separate sets of busbars being necessary for the supplies for the main signalling circuits, and the illuminated-diagram circuits, which are fed with low voltage. Fig. 21 shows the relay racks with the relays and wiring in position.

In the signal cabin the interlocking frame is enclosed in a steel casing which also incorporates a booking desk and the telephone instruments; the latter are thus ready to hand when the signalman is making entries in his register. For the whole of his period of duty the signalman has to remain in the signal cabin and has to take his meals there at convenient times. It was thought desirable to provide some facilities for the signalman to store his clothes, cooking utensils and other requirements, rather than have them placed indiscriminately about the signal cabin. Accordingly, a separate room was provided where each signalman has a locker for keeping his personal belongings, as well as a sink with running water, shelves for storage, and a coat rack, etc.

The walls and floor of the signal cabin are tiled, with special recesses to take all the signalman's necessary equipment. The room is thus easily cleaned and is always tidy (Fig. 22).

(14) THE ILLUMINATED DIAGRAM

The illuminated diagram is an important part of the fittings of the signal cabins and has been of the cut-out strip-light type since its inception in 1905. Slight modifications have been made in the design of the diagram employed, but basically the same type has been in use for many years. This comprises a paper plan mounted between two panels of glass. The sections representing the track are cut out, leaving clear spaces illumin-



Fig. 22.—Interior of modern signal cabin.

ated by small lamps mounted at the rear for the full length of the track. Tests have been made with alternative types of illuminated diagram, but for the convenience of signalmen operating busy services no other type offers such satisfactory indications. In recent years, the introduction of miniature screw-type 12-volt lamps in the diagram has enabled the width of the illuminated strip to be reduced, thus improving the clarity of the plan.

The feature that for a considerable time was an objection to this type of illuminated diagram, namely the reflection in the front glass of objects and lights in the signal cabin, has largely been overcome by using a lightly-acid-washed glass for the front. This has removed the shine from the glass without seriously affecting the clarity of the diagram.

Where route-controlling signalling is employed, the diagram indicates the lie of points by a small dark patch on the illuminated strip. The line for which the points are set shows as a continuously-illuminated strip, whilst the diverging route has a short dark section close to the points. By interconnecting the lamps in these special sections with the point-indication relays, the dark patch is transferred from one strip to the other as the points are operated (Fig. 23).

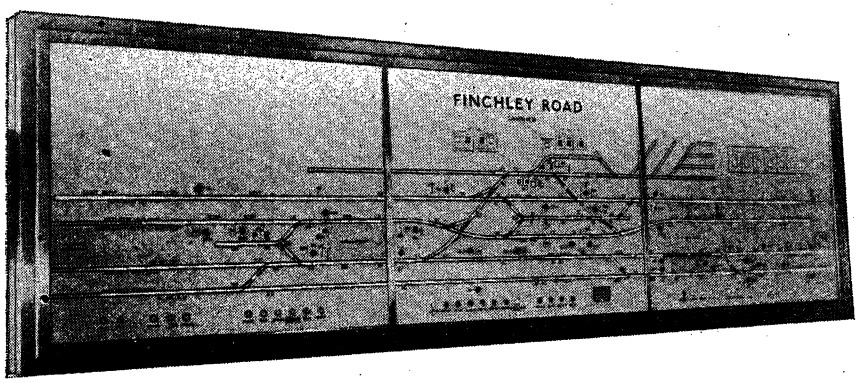


Fig. 23.—Signal-cabin illuminated diagram.

(15) RELAY INTERLOCKING AND ROUTE CONTROL SIGNALLING

Relay interlocking was first introduced on the Board's railways at a small signal cabin at Wood Green in 1932, where an arrangement was incorporated for control of the signalling by the train describer, making a signalman unnecessary for this duty. A connection was made to the train-describer receiver so that when the description showed that the next train was to be reversed, the points were automatically set and the train signalled into the siding. Similarly, operation of the train describer was arranged to signal the train out of the siding into its proper sequence in the service.

The first installation of route-control signalling with relay interlocking was put in at West Kensington in 1934. Here the signal cabin is normally switched out and the service operates straight through, but there are occasional moves to sidings. By providing relay interlocking with remote control operated from an adjacent signal cabin about half a mile away, the signal cabin need not normally be manned. Since that time, route-control signalling with relay interlocking has been adopted in five further signal cabins which have been erected.

It is believed that the combination of route control with relay interlocking has proved of considerable help to the signalman in dealing with a close service of trains. With route control, one lever movement serves to set one or more pairs of points and to clear the associated signals, thus saving the signalman actual lever movements. The reduced number of levers means that all the levers necessary are practically within reach of the signalman from his central booking position.

The arrangement of the relay-interlocking system facilitates the signalman's operation of the frame, as although interlocked levers are still employed, they are not electrically backlocked, all the locking being done on the relay-interlocking circuit. The signalman can therefore operate the appropriate levers to set up a fresh route as soon as the front of a train has passed the signal controlling the route previously set up. After the signalman has reset the levers, the passage of the first train, when it clears the appropriate track circuit, completes the circuit necessary for the points to be thrown and the signal is cleared for the new route. Thus the signalman does not have to stand with his hand on the lever waiting to make a movement immediately the track circuit clears, but can be performing other duties, such as telephoning or entering up his register.

A typical example of a layout in which relay interlocking and route control are employed is that at Finchley Road, where a new signal cabin was provided in connection with the extension of the Bakerloo Line. The layout controlled from this signal cabin is shown in Fig. 23; it comprises a total of 34 signals and 23 points, the whole controlled by 24 route levers. Mechanical interlocking is retained between the levers and push-pull levers are used, as this reduces the number required. Mechanical locking does not really perform any specific safety function, but is very convenient for providing a reminder to the signalman should he endeavour to make an incorrect move or to operate a conflicting lever before the previous one has been reset.

Fig. 24 shows a typical control circuit for a signal in a route-control installation. The control circuit shown is for signal MD 25H, and as indicated on the layout this is a disc signal reading back into a reversing siding. The electrical interlocking comprises circuits incorporating lock relays. Each signal has a lock relay, which is de-energized immediately the signal shows clear and can only be energized again when all conflicting circuits are closed. The lock relay, in turn, is detected in the energized position by the circuits of conflicting signals. The lock relay MD 25H, together with its controlling circuit, is shown at 25H LR. A special feature, which has been added to the circuit and ensures that the train has completely travelled through the route before the lock relay can be again energized, is the route-checking relay shown at 25H UCR. This relay is de-energized as soon as the train passes the signal and cannot be energized again until the train has proceeded through the route and is standing on track GM. 25H LR requires 25H UCR to be energized to permit the former to be energized in its turn; the completion of the movement by the train is thus proved.

It will be noted that the signal control proper includes contacts on both the point-detection relays shown at 46 KR and point-control relays shown at 46 WR—similarly, 53 KR and 53WR.

The current for the signal-control circuit originates from the main signal-cabin busbars and returns to the signal cabin NX, whilst the signal and trainstop indication circuits shown at 25H GCR and 25H VCR originate from the winding of a transformer located at the signal and return to the NX of that transformer. This, together with the individual lead-covered cables previously mentioned, provides a safeguard against false feeds between one circuit and another.

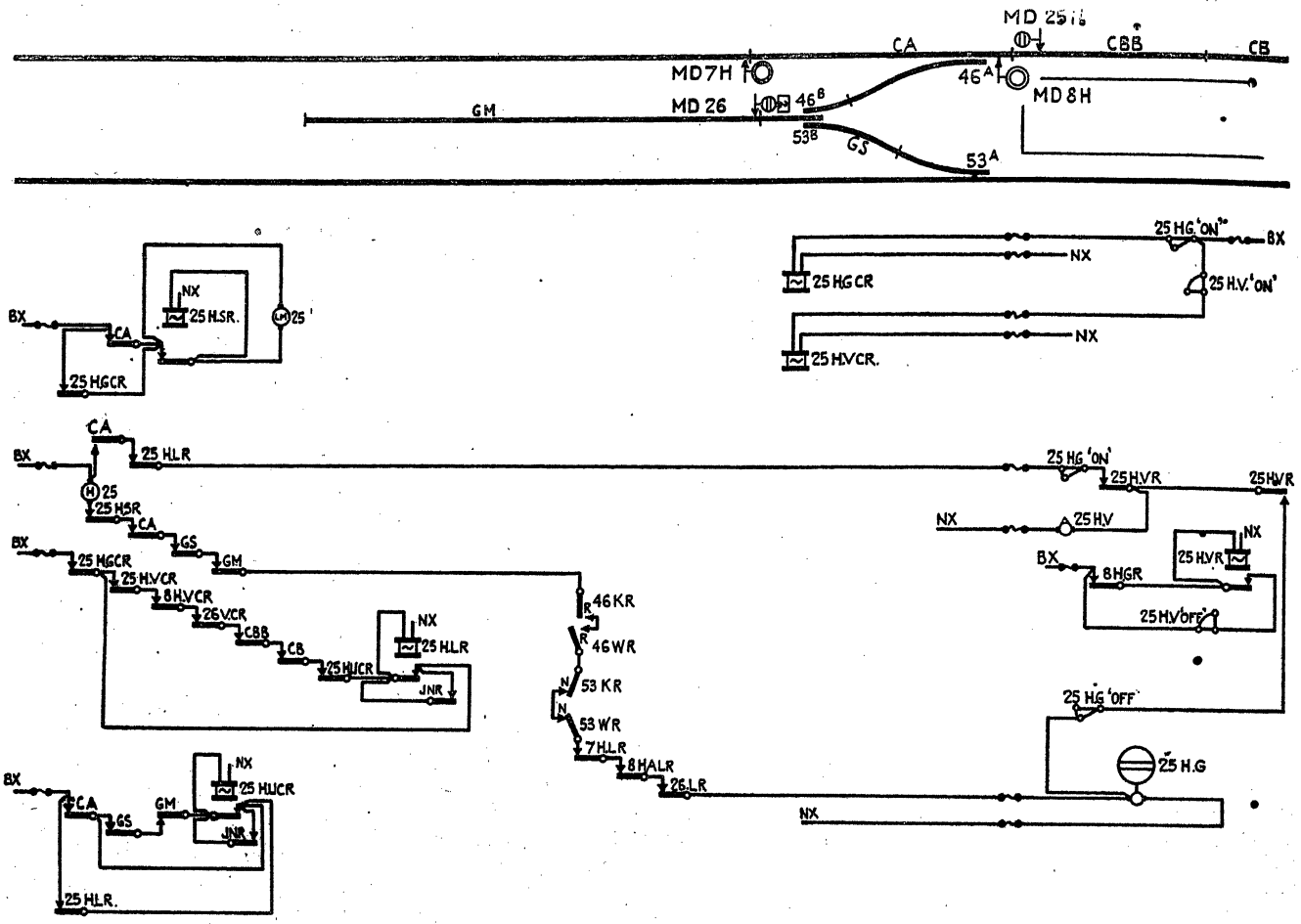


Fig. 24.—Route-control signalling circuit.

SR = Stick relay.
GCR = Signal-proving relay.
VCR = Trainstop-proving relay.
G = Signal.
GR = Signal relay.
V = Trainstop.
VR = Trainstop relay.
CA, GS, CBB, etc. = Contacts of track relays.
LR = Lock relay.
UCR = Route-proving relay.
JNR = Time-release relay.
ALR = Approach lock relay.
KR = Point-position detector relay (in signal cabin).
WR = Point-control relay.
BX = A.C. supply, feed.
NX = A.C. supply, return.

Fig. 25 shows a typical point-control circuit for electro-pneumatic points. The point valves are shown at 46ANW and 46BNW; these are the normal ones, while 46ARW and 46BRW are the reverse point valves. The points are fitted with electric tracklocks on the actual point layouts, and are shown at 46AWJ and 46BWJ. The point-control relay is shown at 46 WR, and all the electrical interlocking circuits are contained in the controls to the operating coils of this relay. The relay serves to maintain current on the point valves until the relay position is changed by one of its coils being de-energized and the other coil energized, when the relay throws completely over. The contact shown at N 46 WR is now broken and contact R 46 WR on the circuit to the point-control valves is made, causing the points to operate. These contacts, normal or reverse, as the case may be, maintain current on the valves even though the control circuits to the point-control relay are interrupted by the opening of relay contacts contained in the various interlocking circuits.

In the circuit shown, provision is made for the points to be operated by a separate lever included in the frame for testing purposes; the locks on this lever are shown at 46(NB)L and 46(RD)L, while the lever contacts shown arise from this separate lever. It has already been considered whether this separate point lever is really necessary, and on a small installation recently brought into service emergency point levers have been omitted.

(16) POWER-WORKED-LEVER REMOTE-CONTROL SYSTEM

The use of relay interlocking helps the signalman in the operation of the traffic, but it has the disadvantage that the circuit employed must of necessity be much more complicated than with individual-lever signalling. While the standard of reliability has been appreciably raised, nevertheless failures may still occur occasionally, and with the more involved circuits delays to traffic tend to be longer than where a simpler system of signalling is employed. Moreover, an alteration to the circuit necessitated by variations in the track layout or additions to the signalling involves very careful workmanship and elaborate testing to ensure that no mistakes have been made.

In an endeavour to overcome these difficulties, a fresh arrangement of remote-control signalling was evolved just before the war. One small signal cabin has been brought into service, utilizing the new system; another has been constructed, although it is not yet in service. This new system is particularly adapted for the remote control of signalling from a distant signal cabin.

Alternatively, for the control of a large layout from a central signal cabin, it allows the signalling equipment to be broken up into several small units.

Here a number of small signal cabins are provided, suitably located in relation to the points and signals to be operated. At each an interlocking frame is installed, with mechanical inter-

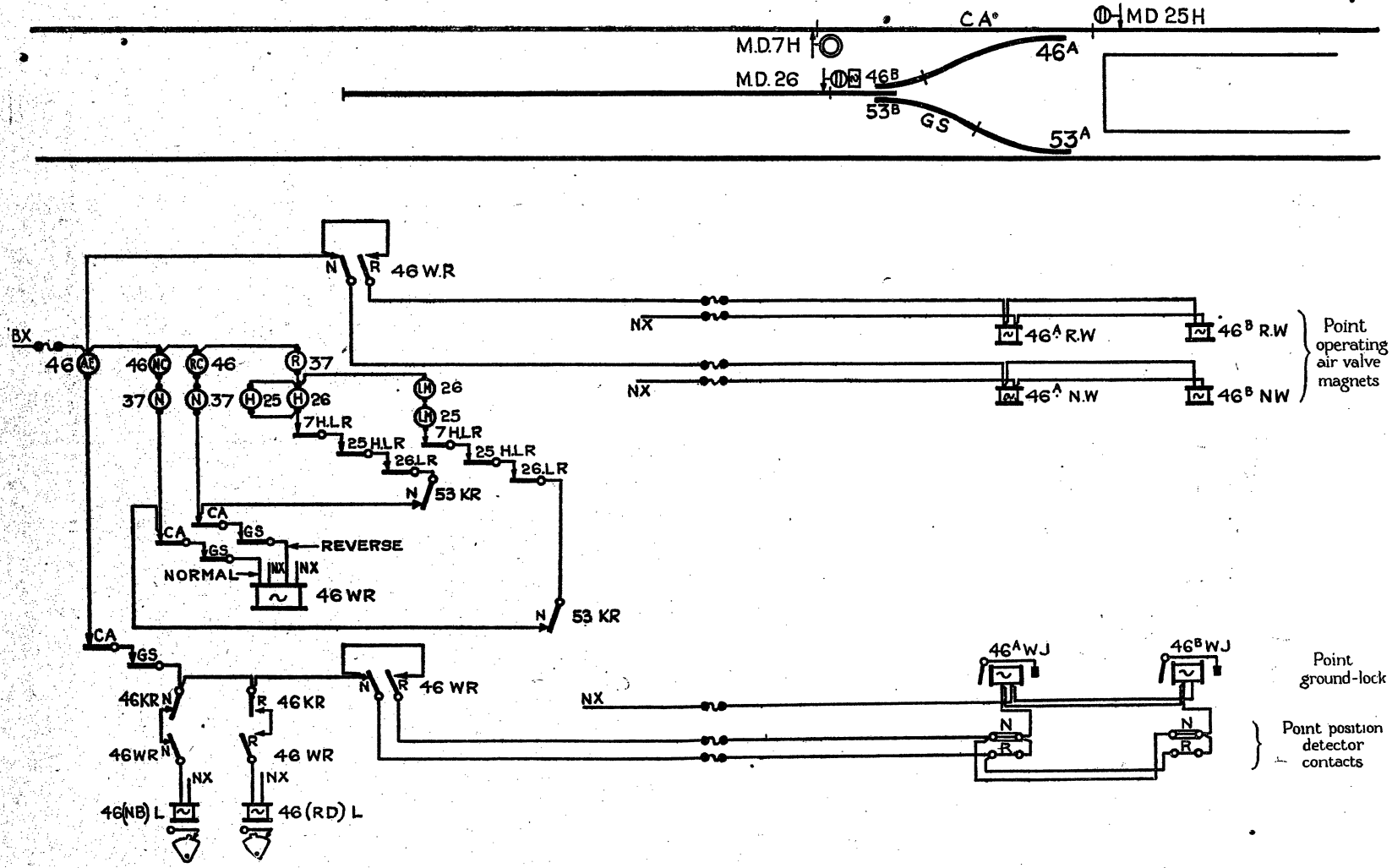


Fig. 25.—Route-control signalling point circuit.

WR = Point-control relay.
NW = Operating magnet to "normal" position.
RW = Operating magnet to "reverse" position.
LR = Lock relay.
KR = Point-position detector relay (in signal cabin).

CA, GS, etc. = Contacts of track relays.
BX = A.C. supply, feed.
NX = A.C. supply, return.
(NB)L, (RD)L = Electric locks on point lever.

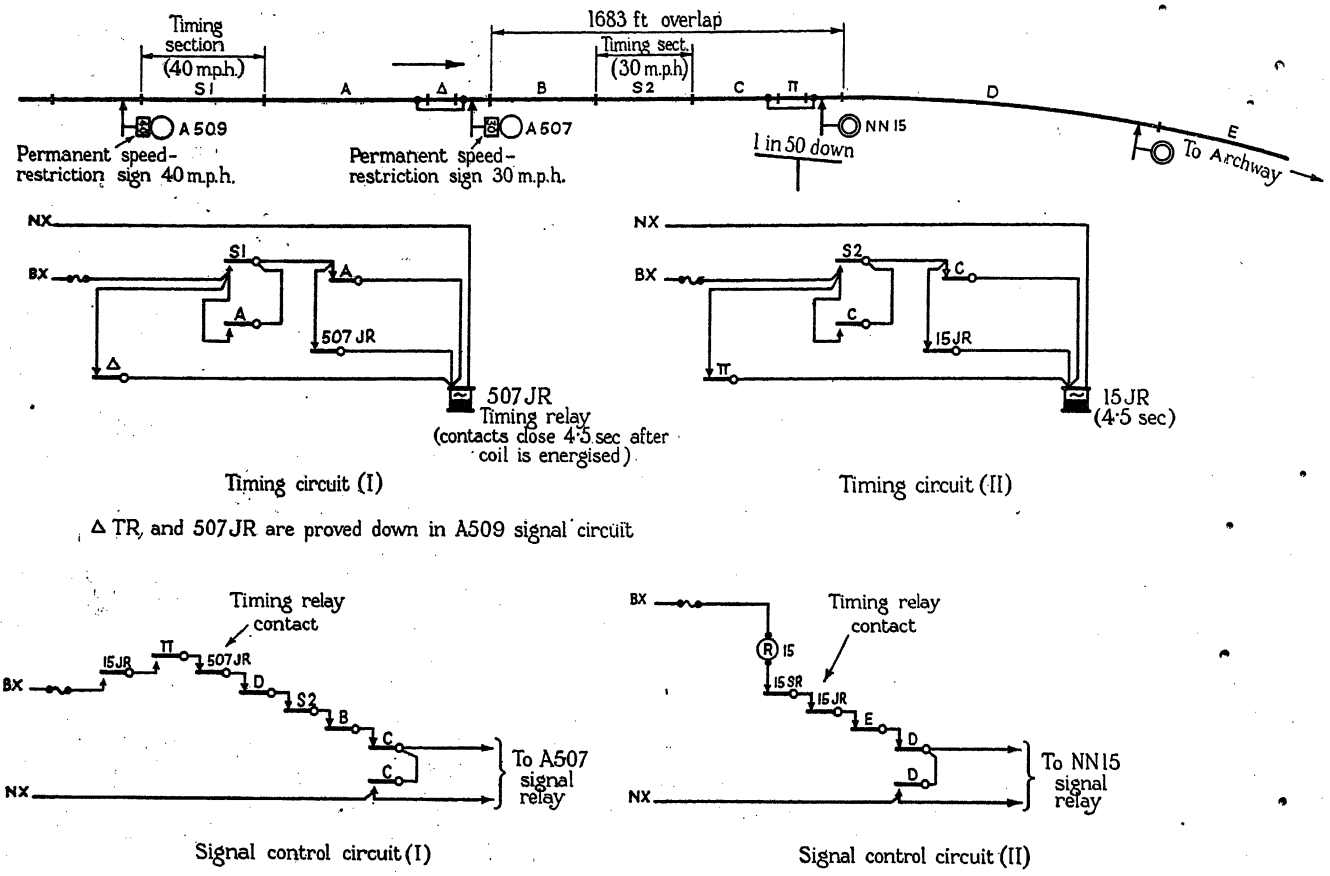


Fig. 26.—Northern Line, Highgate to Archway, speed-control signalling.

A, B, etc. = Track circuits. S1, S2 = Timing track circuits. JR = Timing relay. Δ, π = Rail circuits. BX = A.C. supply, feed. NX = A.C. supply, return.

locking of the levers and electrical backlocking and track locking, as well as with full track-circuit control of the signalling circuits.

Individual levers are employed for the signals and points, and all the levers on the frame are arranged to be power-operated so that they can be operated from some remote point. In the design already adopted, this is achieved by adding small electro-pneumatic cylinders to each lever—one cylinder arranged to move the lever from normal to reverse, and a second to move it from reverse to normal. Thus the whole of the controls can be concentrated in a central control tower where the arrangement can be route controlled in any way desired and the circuits arranged to operate the appropriate levers at the local signal cabins.

(17) SPEED-CONTROL SIGNALS

The use of speed-control signals on the Board's railways as a means of facilitating traffic movements has been considered from time to time, but has never been adopted. With the opening of the extension of the Tube from Archway to East Finchley, it was thought that special arrangements to ensure the observance of the speed restrictions were necessary on account of the 15-chain curve at the bottom of a long section of 1 in 50 down-gradient. Consequently, the signals have been arranged to exercise speed control on the trains passing over the section. Fig. 26 shows a plan of the section and also the control circuits of signals A.507 and NN.15 which are provided with the speed-control feature.

The system arranges for the speed to be brought down to

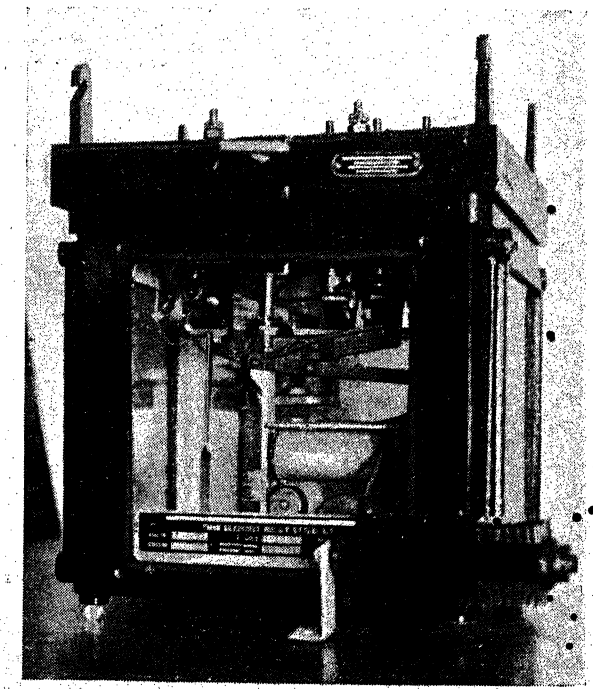


Fig. 27.—Time-element relay.

30 m.p.h. in two stages. Signal A.507 checks the speed to below 40 m.p.h. and signal NN.15 checks the speed to below 30 m.p.h. Illuminated speed-restriction signs are provided, reminding the driver of the need to reduce speed. The speed-control signals are kept at danger until the train has passed over a timing section and the speed has been registered by the time-element relay at below the required value. Immediately this happens, the signal concerned clears. The timing sections are shown as S.1 and S.2 on the diagram.

In the event of the train passing over the timing section at a speed in excess of the speed limit, the signal concerned remains at danger and the driver is compelled to stop at it. Should this happen, provision is made by a rail circuit adjacent to the signal for the signal to clear after the train has come to rest, so that complete interference with traffic movements does not occur.

A special time-element relay, which is shown in Fig. 27, has been developed for use on sections of this sort. The relay is actuated by a clock-type synchronous motor driven from the signalling supply. The relay is adjusted to a fixed time interval maintained at $4\frac{1}{2}$ sec. The variation necessary to fit in with the required speed restriction is obtained by altering the length of the section. Section S.1, which is adjusted for 40 m.p.h., is 264 ft in length; while section S.2, which is adjusted for 30 m.p.h., is 198 ft in length.

(18) CONCLUSION

The trend of development in any signalling installation must be primarily to improve the safety factor of the equipment and to ensure that everything possible is done to avoid any improper working of the equipment likely to cause an accident. Nevertheless, constant attention must be given to the need for improvement in the reliability of the equipment in service, so that delays to traffic are reduced to the minimum.

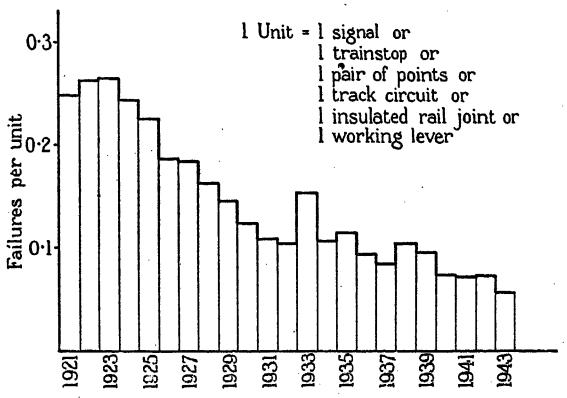


Fig. 28.—Total failures per unit.

Fig. 28 shows the failures per unit per annum from 1921 to 1942 and indicates the progress that has been made in improveing the reliability. The slight tendency of the failures to rise in 1938 and 1939 was due to a period of extensive alterations to the signalling systems and the addition of new equipment which took some little time to settle down.

DISCUSSION BEFORE THE MEASUREMENTS SECTION, 17TH MARCH, 1944

Major L. H. Peter: This paper is one which provides a record of the application of well-known principles to a large system. Basically, the system described is still the same as that installed in 1904, namely the two-aspect signal system with repeater signals controlled by track circuits and with train stops at the signals to enforce obedience. Point operation throughout the period has been based on the electro-pneumatic system.

Although the system has remained the same, the apparatus and the circuits have undergone considerable development. Many of the appliances used are peculiar to the requirements of the dense traffic of the system, and throughout the paper there is clear evidence of the great attention which has been paid to achieving the utmost security and reliability of operation in every detail.

There are a few points on which one wonders whether, if the system had to be re-signalled, the same methods would be adopted.

In Section 5, curves of the relative cost of track circuits, etc., for all third- and fourth-rail systems are given, based on 1936 figures. Some statement as to the frequency of the supply for the signalling system on which these were based is desirable, because the cost of impedance bonds, which is the major item in the third-rail traction system, is to some extent dependent on this. Raising the frequency of the signalling supply with third-rail traction might be of considerable advantage in the future. As many transformers in signalling systems would also be reduced in size, and in view of the relatively short track circuits normally used in this country, rail impedance is not a vital matter. The upper limit of frequency that can be used with advantage depends on whether any of the signalling apparatus requires small a.c. motors. The proposed increase in frequency also tends to reduce the capacitance required in feed and resonated systems.

It is possible that, when considering an entirely new installation as distinct from the development of an existing installation, recent developments in coded track circuits might represent a large saving in cable, and might provide means for giving a signal in the cab and enforcing speed control without necessarily using the mechanical trip-arm. Such a system of track circuiting also offers some security against extraneous alternating current, mentioned in Section 9.2.

Another point is the modern method of drying air, which avoids the use of the spirit injectors shown in Fig. 14.

One or two symbols have crept into the chart which are not included in the standard nomenclature of the B.S.I. If these symbols are necessary, that Institution might consider making these additions so that we can keep our signal language complete.

One of the most striking features of the system described is the high degree of reliability of the equipment, as shown by the failure chart in Fig. 28. When this chart is related to the train mileage it is seen that a unit piece of signal apparatus, or a group comprising a unit, is called upon to operate very frequently over a period of very many years without any sign of failure. This is a testimony to the efficiency of the system, the apparatus and the maintenance engineers, which should not be disregarded.

Mr. F. H. D. Page: Not only has a signalling circuit to be designed to perform a definite function, but it is essential to prove that that function has been performed in the way intended and, further, that no fortuitous conditions shall adversely affect that function. While this implies a certain degree of complication, over-complication brings its own disadvantages, and the engineer has to decide just how far it is really practicable and economical to go. For instance, in the automatic signalling circuits in Fig. 4, the berth track relays are provided with back contacts for coupling to NX. While this may give protection against a false feed or the accidental bridging of track relays 99b, 99b and 101b, it may not be effective if, for some reason, the resistance of this contact becomes too high to blow the fuse. It is therefore questionable whether this refinement is really justified. Has this contact proved useful, and has any particular attention been given to its maintenance?

The author's arguments for a special frequency for signalling circuits and for two-cored cables, instead of multicored cables, do not justify the enormously increased cost of adopting these features on the main-line railways, particularly in view of their long experience of standard frequency and multicore cables in large power and automatic installations. His design of a screened multicore cable will do little, if anything, towards bringing the cost within practicable limits.

Much controversy has centred round the merits of all-electric and electro-pneumatic operation. There is a great deal to be said for the simplicity and reliability of the latter so far as point operation is concerned, and it may be particularly suited to the Board's conditions. The author refers to experimental comparisons made on a signalling section; can he give figures of the comparative costs of the two systems? The possession of a pneumatic system has certainly enabled him to introduce the power-worked-lever remote-control system described in Section 16, but, even so, I cannot see the advantage gained over remote control as installed on the Great Western Railway.

Has the author found abnormal deterioration of the lead cable sheaths owing to vibration, and what is the average life of these cables on tube lines and on open-air routes?

Mr. S. W. Melsom: The paper is admirable from the point of view of railway-signalling apparatus, but I am a little dubious concerning some of the author's remarks about cabling. In Section 10, loss of lead on passing the cables underground is mentioned. This appears to be a clear case of electrolysis, due to d.c. earth currents from the earthed rail: a quite common experience with trams where feeder or transmission cables were laid alongside or near the track. The effect of the electrolytic action might easily be mistaken for burning.

The author refers to the cure for the trouble. I suggest that by putting his cables on posts he has taken them out of the lines of leakage current flow. The cables are not now earthed but are well bonded, and the method could be further improved by inserting a piece of insulating material at each supporting point. Bonding the cable sheaths back to the signal cable is probably a much better method than attempting earthing under these conditions.

The author's description of his proposed new type of multicore cable is most interesting, though I am surprised at the reasons which appear to have brought it about. In my opinion, a straightforward multicore cable could and should be wholly satisfactory; perhaps, however, we may expect consultations on these matters with a view to providing the best possible type that can be devised for these very important services.

Mr. E. G. Brentnall: As the author points out, conditions on London Transport are very different from those of the main-line companies, and this affects the type and operation of the signalling system adopted. He states that the electro-pneumatic installations of the Board's system are simpler than all-electric ones and hence are easier to maintain. But with an electro-pneumatic installation there are two sources of power to be provided, and the main-line companies could not therefore economically operate electro-pneumatic gear, except at certain locations.

The double feed to the red signal lamps is interesting. On the London and North Eastern Railway the contacts feeding signal lamps are duplicated, wherever possible. What is the method used on London Transport railways for changing lamps? On the L.N.E.R., independent double-filament lamps are standard, and only one filament is lit, so that when the main filament fails the second filament is brought in automatically. The lamps are inspected at least weekly and remain in use until the main filament fails.

The fourth-rail traction system is simpler from the signalling point of view as it does away with the necessity for impedance bonds, but I am surprised at the financial advantages claimed over the third-rail system. As main-line systems usually have fewer track circuits per mile than the Board's system, the difference in cost between the two traction systems would probably not be so marked on main lines.

With regard to the signalling cables, there is much to be said for multicore cables, and the possibility of failure by breakdown is very remote. The burying of cables also offers many advantages, provided they are buried in the proper place and due precautions are taken.

I believe there is a great future for relay interlocking or its equivalent, but in my view the panel system with the switches situated on the panel is better for main-line conditions. This is a controversial point, but the system has certain definite advantages as to convenience of operation.

I was particularly interested in Fig. 28, showing the progressive reduction in total failures per unit over the last 23 years. This is a matter of congratulation to the author, and is a very creditable achievement.

Mr. H. H. Dyer: I believe that the multicore cables with which trouble was experienced were v.i.r. insulated. The multicore cables used by the L.M.S. Railway for signalling are oil-impregnated-paper insulated and there is a very large factor of safety, the works test voltage being 3 000 volts r.m.s. for 15 minutes, against an actual working voltage not exceeding 110 volts r.m.s. Such cables have been in use for as long as 35 years and have given no trouble. I cannot agree that the additional cost of single- and twin-core cables is justified.

Referring to Fig. 17, the author has shown a fault between two conductors on the BX side, but I would point out that if he had included control contacts in the NX side as well, two failures would have been necessary at exactly the same instant on two chosen pairs, to set up a dangerous condition. The circuit shown in Fig. 18 is not immune from the same trouble, as absolute reliance is placed on the earthing of the NX side of the supply. If this should be inefficient, a contact between a BX wire and the sheathing in each of the two cables could result in precisely the same condition as that shown in Fig. 17.

The lead-covered signalling cables used by the L.M.S. Railway are protected by two layers of oiled paper and two layers of bitumen-impregnated hessian, which provide adequate protection to the lead sheathing against the effects of electrolysis and chemical action.

Although the use of higher frequencies is possible on the London Transport lines, the main-line railways have signalling installations all over the country, and obviously had to adopt 50 c/s as no other frequency is available.

Mr. S. A. Stevens: I think that Figs. 17, 18 and 20 are worth further discussion, as they concern that part of the subject relating not merely to signal engineering but also to general electrical problems. Many signal engineers believe that the best principle is not to earth the NX, but to keep the whole system insulated from earth and then to install leakage indicators to prove the insulation of the system. The author has chosen an arrangement whereby some point in the power system is connected to earth so that a fault on the other side of the system clears itself by blowing a fuse. Relying on the blowing of a fuse means relying on a low-resistance fault, and one may then have to wait for a fault to drop to a low-resistance level. If the system is not earthed it may be kept running although the fault may be developing, and a warning may be given of a developing fault while it is still convenient to deal with it.

I am aware that the author has in the past used leakage indicators, and I am interested to learn why they have been replaced by fuses. I believe that the system used at one time was a de-

velopment of the old system used by d.c. power engineers, with two lamps connected in series across the positive and negative sides of the system with the mid-point earthed. This demonstrated, not that the insulation was sound, but only that both sides were equally insulated: yet there may be faults on both sides which counteract each other. Perhaps this was the author's objection to the leakage indicator. If so, has he considered another system in which the NX, instead of being directly connected to earth, is joined to earth through a source of direct current using a high resistance so as to superimpose on the a.c. signal-power system a small d.c. potential fed through a high resistance; by this means a voltage-operated relay, also connected between NX and earth, is energized as long as the insulation of the system as a whole is properly maintained. A fault developing at any point on either the BX or NX sides of the system will be indicated by the release of the relay (British Patent 549511).

Does not the author consider this method of giving a fault indication preferable to waiting for a fault to become a breakdown, and possible interrupt the service?

Mr. H. Bujama (*communicated*): My main interest lies in the apparent challenge thrown out by the author in Section 5 on the advantages of the fourth-rail traction system. To any Southern Railway engineer who knows the success that has been achieved by the third-rail system, the troubles encountered on the Board's signalling system are comparable to those which were expected, but which did not materialize, on our own system. That the Board should be harassed from one system to another by fourth-rail leakage and electrolysis is a distinct disadvantage of the fourth rail, as our signal engineers can assure them that we do not get the same kind of troubles.

Concerning track voltage drop, it should be noted that two track rails have a resistance equal to that of one 150-lb conductor rail, and the supply and bonding of the fourth rail must be more expensive than the mere bonding of two track rails, so that the Board have no advantage in this direction.

While one must admire the cable runs carried out by the Board, it is surprising that this work is necessary because the Board cannot run cables at ground level for fear of electrolysis; our signal engineers run lead-covered cables in the track, although mainly "ite" types of cable are used with success.

In the earlier schemes adopted by the Southern Railway, 75-c/s signal supplies were introduced, but since 1933 long lengths of track have been supplied with 50-c/s signalling, and no interference has been encountered or expected. In the case mentioned, where leakage from an arch was in evidence under the track rails, it is, in my opinion, impossible for such leakage to have interfered with a track circuit. I would be interested to hear what frequency is adopted for signalling in the Board's area, where the C.E.B. supply substations at 50 c/s.

I am intrigued by the author's phrase: "Although the third-rail system can be adopted, and is in use elsewhere." In view of the Southern Railway's 1 700 miles of single track, our last year's car mileage of over 160 million, the number and size of the Southern Railway's power signalling frames, and the number of our traction substations, Southern Railway engineers can assure the author that the third-rail system is in use elsewhere with some success.

Electrification schemes have much in common, and we can learn much from the experiences of each other. We must congratulate the author on the high percentage of accuracy shown by Fig. 28. Southern Railway signalling engineers assure me that they, also, have a high percentage of accuracy, and have to deal with these expensive impedance bonds, and our track rails carry very heavy d.c. currents.

Mr. J. F. H. Tyler (*communicated*): The London Transport system of earthing signalling circuits depends for its success on the use of unserved lead-sheathed cables and on the continuity of the cable run. It would not be possible to adopt this method as standard main-line practice owing to the short lengths of cable sometimes installed.

It would be interesting to know what precautions are taken between open and tunnel sections to avoid full earth being applied to the open section cables.

The London Transport type of twin-cable run unfortunately proves too expensive for general adoption by the main-line companies. It is often claimed that the best method of installing signalling cables is to bury them direct in the ground, which is cheaper and avoids the risk of damage by derailments. In my opinion, this view does not take sufficient cognizance of the many alterations and additions to the signalling scheme which inevitably take place during the life of the cable; or of the possibility of damage due to civil engineering works. Liability to damage due to derailments, in my view, is overrated, and if it does occur the extent of the damage is at once obvious. Damage to buried cables may be undetected for a long time.

I believe that a cable run should be a general-purpose item which should be available for all signalling and communication cables. In the course of time, a great deal more cable will, no doubt, be installed on the main lines to avoid gale and snowstorm damage to overhead lines. It is possible that in the future we may also have to install coaxial cables for carrier circuits to increase the number of channels and overcome the growing difficulty of short cable lengths in the trunk lines.

The policy of burying cables does not facilitate alterations, renewals and additions, and the practice of running cables above ground in the most accessible manner seems much sounder. It is quite possible to provide a single cable run suitable for main-line conditions at a cost comparable with the burying method, and this, I consider, should be done at every opportunity as a long-term policy.

For restricted clearances, the Board's system of concrete surface troughing maintains the principle of maximum accessibility, but objection is often raised that the troughing is subject to the ingress of water and dirt, and perhaps the author would state his experience on this point.

With regard to the provision of satellite power frames in a large remote-control installation, it would be interesting to know what type of failure is envisaged which could be overcome by bringing the satellite into manual operation, seeing that the same safeguards are presumably applied in both cases.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. R. Dell (*in reply*): Major Peter refers to the frequency of supply for signalling, which on the Board's system is 33⅓ c/s. I agree that the use of a much higher frequency would offer advantages. While I have no experience of the behaviour of coded track circuits, I think that the additional apparatus with its attendant maintenance may outweigh the saving in cable. The maintenance required by cable is extremely small, if it is properly installed.

I agree that the circuits through back contacts of berth track relays, referred to by Mr. Page, are not self-proving and leave something to be desired, but they are trifling in first cost, and the degree of protection they give is considered worth securing. I have not available directly comparative costs of the all-electric and electro-pneumatic systems, but I consider that for an intensive installation the latter is cheaper. Its cost per point mechanism is about 50% that of an electric one.

With regard to the deterioration of lead cable sheaths by vibration, no particular difficulty has been experienced with the special alloys designed to resist vibration so long as supports are placed sufficiently close together. Special precautions to protect cables from vibration at difficult points, such as bridges, are taken by suspending the cables on leather or balata straps. An outdoor installation provided just over 20 years ago has begun to show signs of deterioration. Here, the cable bracket spacing is 3 ft 6 in. The conditions in tube tunnels are very suitable for lead-covered cables, and cables have been found in surprisingly good condition after over 30 years' service.

Mr. Melsom draws attention to the possibility of electrolysis causing deterioration of cables installed underground. This is quite probable and might combine with mechanical damage owing to the vibration of trains passing above. I have seen cables damaged by electrolytic action, but I have not confused damage of this type with burning of the cable due to excessive currents, such as sometimes occur with faults in the traction system. I wanted to emphasize that, in moving the cables from underground ducts to positions above ground, they have been brought from a position in which they were liable to damage to one of comparative safety.

In reply to Mr. Brentnall, on the Board's system the signal lamps are of the double-filament type in daylight signals, with both filaments normally alight; in the tunnels two lamps are employed in parallel. Lamps are changed by the maintenance staff following inspection.

Mr. Dyer's suggestions that signalling circuits should be interrupted by contacts on both poles is interesting, but would mean a very heavy increase in the number of relays necessary at, for example, a relay interlocking. I agree that the safety of the signalling system depends to a large extent on the continuity of the earthing of the NX side of the supply, and for this reason the rather elaborate precautions described are taken with this earth connection.

In regard to the comparative advantages of the insulated system of signalling circuits and the system of earthing the NX pole, Mr. Stevens suggests that it is better to detect a fault when it is in a high-resistance state, so that it can be cleared at leisure without interfering with the proper operation of the system. It was just this feature which led to the decision to adopt the earthed system in the Board's signalling. Once a high-resistance fault has developed, it operates the earth indicator and the lineman responsible may leave it for hours, or even days, while busy on some other work; even if he applies himself immediately to the job, locating the actual fault may take some hours. Meanwhile, the leakage indicators have been rendered inoperative by the one fault and will not indicate a second fault, which may develop and create dangerous conditions. In instructions for linemen on what measures to take when the earth indicator shows a fault on the BX side of the system, a warning has to be included that the NX of the system must be earthed immediately the earth indicator shows a fault, so that the system may be safeguarded until the fault is cleared. From this, it appears only logical to adopt the earthed system continuously.

I have no experience of the superimposed d.c. earth indicator described by Mr. Stevens, but from his description it appears to give a much better leakage indication than the two relays with the mid-point earthed. But I do not think that this advantage would outweigh the disadvantages of the insulated system.

Mr. Bujama appears to be under some misapprehension as to the comparison made in the paper between the fourth-rail and third-rail systems. I gave no details of troubles encountered on the Board's signalling system due to the use of the third-rail traction installation with an earthed return. Most of the Board's traction installation from its inception has employed the fourth-rail system. Mr. Bujama states that two track rails have a resistance equal to one 150-lb conductor rail. The measured resistance of a 60-ft B.S. 95-lb running rail in new condition is approximately 0·00063 ohm, so that two such rails in parallel would have a resistance of 0·000315 ohm, whilst the resistance of a 150-lb conductor rail, 60 ft long, is 0·000228 ohm.

Mr. Tyler proposes a general-purpose cable run, which is already the practice on the Board's system. The concrete cable posts accommodate the signalling cables, compressed-air pipes and telephone cables, generally on the track side of the posts, with high-voltage feeder cables from the power houses to the substations, and lighting cables on the other side. The low-voltage traction cables are generally not run on the same posts, as a defect on these cables causes extensive fusing and damage to neighbouring cables so that it is better to keep them away from the signalling and high-voltage cables.

Concrete surface troughing is not as satisfactory as cable brackets, and in my opinion should be used only when the other methods of cable installation described are not available.

Satellite power frames can be brought into service whenever a fault develops between the main control cabin and the satellite cabin. For instance, if the main cabin were completely destroyed by fire or otherwise, the signalling system could be kept running by the satellite frames. They could also be used should a fault develop on cables between the control cabin and the satellite.

DISCUSSION ON "THE FUTURE OF THE DOMESTIC WIRING INSTALLATION"*

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 3RD NOVEMBER, 1943

Mr. R. L. Hewling: As an engineer in charge of a working-class area of supply, I should like to quote a few statistics in support of the authors' contention that facilities should be provided for any tenant to make full use of electricity if he or she wishes to do so. On one of our council housing estates, built in 1938, fairly reasonable facilities were provided in the way of lighting points and socket-outlets, each house being equipped with an electric wash-boiler; the tenants could, if they wished, also hire an electric cooker at the usual rental. Up to date 49% of the tenants use hired cookers, and had it not been for the war this percentage would now be much higher. Nevertheless, the average consumption of consumers on this particular estate is 132% higher than the average domestic consumption of the whole of the supply area, notwithstanding the fact that 22½% of the dwellings are occupied by aged people in three-roomed bungalows. The average consumption of the latter group is 72·5% above the total domestic average. These results are highly satisfactory and fully justify the policy of providing the facilities suggested by the authors. It is my view that the electrical industry must strive to put satisfactory installations in all new dwellings

* Paper by FORBES JACKSON, W. J. H. WOOD, G. SMITH and E. JACOBI (see 1943, 90, Part II, p. 453.

as they are erected, and see that the cost of this equipment is included in the initial price. By doing so the cost will be spread over the period of hire-purchase where houses are built by private enterprise, or over the loan-term period of housing loans where houses are provided by local authorities. I feel that only by spreading the cost over a period of years will houses be adequately equipped for an electrical service, at least in working-class areas.

Regarding protection, I fully agree with the suggestion of single-pole fusing and the elimination of a main installation fuse so that costs can be reduced. The authors mention the possibility of replacing fuses by small circuit-breakers. Why not go a little further and incorporate an earth-leakage tripping device with the circuit-breaker? I think it is highly desirable to provide this added protection for the proposed ring-main and kitchen circuits.

I hope the time is not far distant when the necessary amendments will be made to the Wiring Regulations to incorporate the many suggestions put forward in this paper.

Mr. W. E. Dalby: The proposals in both parts of the paper are very sound and should lead to the desired development of the domestic load. In the past one of the main difficulties in developing the water-heating and cooking loads has been the inconvenience and cost of installing the necessary circuits. The suggestion that conduit should be installed for such apparatus, whether or not that apparatus is to be connected in the first instance, is certainly a step in the right direction.

I cannot agree with the suggestions in Part 1 that an attractive low rate be given for water heating in the summer and that the control switch should be locked off during the winter. Such a restriction is very undesirable, and I can foresee objections to paying hire charges for the period when the apparatus cannot be used. Another difficulty would be that a low rate would rule for water heating in the summer months, and would introduce a metering problem. Either a second meter would then be necessary, or the unit charge of the multi-part tariff would have to be lower in summer than in winter.

The combined service equipment has much to recommend it. In the supply authority's view it is no doubt very desirable, but is not the attainment of such equipment to some extent impracticable at present and likely to remain so until the tariffs of many undertakings are revised? Many undertakings have in operation two flat-rates for domestic premises, namely, a high flat-rate for lighting and a low flat-rate for all other purposes, in addition to some form of multi-part tariff. A house may be equipped with the simplified service equipment and its attendant simplification of the circuit wiring to the satisfaction of the first consumer. But a new tenant may decide to avail himself of the two flat-rates, with the result that the simplified metering equipment has to be altered to the present haphazard arrangement.

I suggest that tariffs for domestic premises be limited to three, namely two two-part tariffs—one with a comparatively high fixed charge and a low running charge, the other with a low fixed charge and a high running charge—and a block tariff based on the first of the two-part tariffs. These tariffs would cater for all classes of domestic consumers and would enable all the benefits of the simplified wiring system to be reaped by both the consumer and the supply authority.

Mr. H. V. Field: The proposal to "clean up" the service equipment by a standard equipment of good appearance is timely. Such equipment, housed in a plastic case, can be put in an accessible place without offending the eye, instead of being relegated to some gloomy and inaccessible place, such as the cupboard under the stairs. Fuse-carriers might also be redesigned to permit easy rewiring without recourse to screwdriver and pliers.

The arrangement of conductors in the skirting board is reminiscent of the wood casing and capping of an earlier day. What arrangements are proposed at places such as doorways and fireplaces? Is a similar system proposed for lighting circuits, or is the retention of conduit anticipated—this would give a mixed system which can hardly be regarded as an ideal? Embedded metal strips in skirting boards would lead to a multiplicity of joints, and drawn-in conductors would be preferable, unless all joints were sweated. Screwed joints with thin copper strip are not satisfactory.

Part 1 advocates 10-amp fused plugs, whilst Part 2 suggests the elimination of local fuses at plug points. Reasons in support of the second arrangement would be appreciated. Part 2 also advocates a limit of 2 000 watts per circuit—I regard this as low, and would suggest 3 000–4 000 watts as more reasonable.

Mr. J. B. Lancaster: Regarding the difficulties experienced in the use of h.r.c. fuses, particularly in the supply company's cut-out as back-up protection to the normal rewirable type of fuse, there is evidently a great lack of reliable discrimination between the main and sub-fuses in such a layout owing to the inherent quick action of the h.r.c. fuse under fault conditions. I suggest that the installation of these fuses is, in many instances, purely a fetish. I am not condemning the h.r.c. fuse. There is no question that, in many instances, the short-circuit current available at the service termination necessitates its use; but I do suggest that the use of an h.r.c. fuse and rewirable fuses in the same piece of apparatus, as in Fig. 3, is wrong. Either the short-circuit duty is high enough to demand the use of h.r.c. fuses for the main and sub-circuits, or, if it is not, more reliable discrimination is obtainable by the use of rewirable fuses throughout. It should, perhaps, be noted that, while lack of discrimination may result from the use of a cartridge fuse as the main fuse and a rewirable fuse as the sub-fuse, better discrimination is obtained by the reversal of this arrangement. It is often convenient to embody a cartridge fuse for local-circuit protection (as in a fused plug), and there can be no objection to this practice.

I think the authors should be taken to task for their advocacy of the universal use of 5-amp plugs with circuit loadings up to 15 amp, or rather for their failure to quote any actual operating experience in support of their views. I do not agree that a reasonable millivolt-drop figure is in itself a sound criterion on which to forecast contact performance.

Mr. J. C. B. Nicol: I think this paper is much less useful than it might have been. Part 1 is useful as it calls attention to some sound principles which could be adopted at once, namely ring mains, universal sockets, standardization of service arrangements, etc. On the other hand, Part 2 falls quite a long way short of what should have been aimed at. The main object of a paper such as this should be to make known to house designers, house builders and house users all the possibilities of electrical services and the requirements for their safe and economic installation.

The laymen who read this paper will not appreciate the territory prescribed by the word "Wiring" in the title, and will accept this paper as the latest expert information on the future of all domestic electrical services.

The authors have departed from purely wiring considerations to give one suggestion for a comprehensive kitchen unit. I think this paper would have been much more useful if they had ignored the title still further and recorded the possibilities of clothes drying and airing cupboards, powered ventilation of cooking fumes, small buffs for cleaning pots, air-conditioning apparatus, etc.

I do not agree with the arrangement of the kitchen equipment as illustrated, The food cupboard is too near the sink and refuse bin. The cooker, too, should not be adjacent, and the unit seems to have many inaccessible nooks and crannies for collecting dust. I think the *kitchen room* should be designed as a unit with the

cooker, sink, cupboards and tables ranged around and incorporated or provided for in the structure.

Mr. J. J. L. Murray: In Part 2, Section 4.2, the authors say "plaster is not really suitable—it holds dust, it cannot be easily cleaned, and it cracks," and continue later—"a really suitable wall surface will not only be clean, strong and easily washable, but it will be designed for the express purpose of providing heat and sound insulation." I can sympathize with the authors on their first point since, in the smaller dwelling houses, I have seen many bad examples of walls and ceilings; but this does not make the authors' statement correct. Plaster cracks when its support cracks, which is quite another problem. It is a matter of design, workmanship and the use of the correct materials for the job. The second part of the statement infers that a surface as defined is not possible with plaster. But hard, smooth, joint-free, washable walls essentially made of plaster do exist.

The authors suggest that the ideal wall can be produced from plastics. The possibilities of plastics are great but there are many difficulties to be overcome before building on a large scale with such materials becomes practicable. It seems to me inevitable that future building programmes will be almost wholly dependent on normal building materials, namely bricks and mortar, no matter how attractive the use of plastics may appear, especially since post-war building programmes are likely to commence long before the plastics industry can cope with the demand.

We must therefore face the problem of efficient wiring installations, based on the use of existing building materials for a long time yet; in consequence I think it is unwise to condemn plaster in such specific terms.

[The authors' replies to this discussion will be found on pages 431 and 432.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 22ND NOVEMBER, 1943

Mr. P. Ward: I agree with the suggestion in Sections 3, 4 and 5 of Part 1 that in property to be built immediately after the war we should aim at the most complete wiring installation possible. If the necessary circuits have been provided, the equipment can be put in later. I agree with the suggested general utility sockets, but they must be big enough to carry the largest pieces of portable apparatus likely to be found in a house. They should be suitable not merely for small apparatus, such as irons and radio; in my opinion, the 2-kW maximum capacity is not sufficient—3 kW should be provided so as to cater for the washboiler and the smaller types of existing cooker. As suggested in Section 6, conduit should be provided for a cooker circuit, though I would prefer to install a complete circuit even if all the plug points desirable could not be put in.

One ring main in the whole house, as proposed in Section 10, will lead to trouble, especially when the consumer wishes to become "all-electric," which he may be deterred from doing if there is one ring main.

I disagree with "flexing out" as indicated in Section 14. The less "flexing out" there is, the better for all concerned; an adequate number of outlets is the only proper solution.

With regard to Section 15, we must agree that in the past service gear has not been all that it might be. The consumer's main fuses can, in a properly-planned installation, be omitted as the authors suggest. The suggestion for service boxes is good and has been included in some recommendations sent forward from this area for consideration by the Installation Committee.

With regard to Section 15.7, the wiring of flats in particular is a difficult proposition, but the chief difficulty is in getting adequate rising mains installed. The authors say this matter should be the subject of agreement between the owner and the supply undertaking, but they do not indicate how such an agreement can be arrived at, either with regard to installation or to maintenance.

On the whole, I am afraid the authors' suggestions mean further complications in wiring and accessories, and except for the provision of improved service gear, we had better leave things as they are until we reach the stage visualized in Part 2 of the paper. Here the authors tackle the problem properly and I agree with nearly all their recommendations.

I do not think they are quite right in suggesting in Section 3 that the lighting load is proportional to the floor area. In some of the smaller post-war houses, rooms will be 8 ft or less in height, and the value of ceiling reflection will be different from that in higher rooms.

It will probably be necessary to have two types of kitchen, one the combined living-room and kitchen of small houses and the other the kitchen proper of larger houses. For the latter, an arrangement as in Fig. 1 might be possible but I am rather sceptical of these assemblies. They look nice when new, but what will they look like in, say, five years' time? Much will, of course, depend on the type of materials chosen.

The authors appear to prefer individual drives for all power-operated kitchen equipment. In the smaller houses there is much to be said for a utility motor which can be taken to the various pieces of equipment or vice versa. Though not quite so convenient, it would give a considerable saving on capital cost which is an important item in the small house.

I do not think the consumer's fuses should be located in the service box as suggested in Section 4.3.1. Mains should be run in built-in ducts from the service box to central points on each floor. Each floor should be entirely self-contained and lighting should be split horizontally and not vertically. On a floor where there are plenty of plug points the risk of being left entirely in the dark is very remote. In the wiring system in Fig. 4, the lighting is taken from the ring and any fault on this main will put the whole room in darkness.

I do not agree that 5-amp plugs can be safely operated at 12 or 15 amp as suggested in Section 4.3.4. Though the individual pins may carry the greater current, the complete assembly cannot be relied upon to do so, owing to the necessary tolerances. I agree that there should be only one size of socket-outlet and that this should be of 15-amp capacity. The only exception should be 2-amp socket-outlets in the lighting installation only, for lamps, clocks and radio. Three such 15-amp socket-outlets per room will meet normal requirements, if they can also take the 2-amp or 5-amp plug tops. This can be done with an existing make or flat-pin plug; it should be possible to design an adjustable type of round pin fulfilling the same purpose. Further, if the 15-amp plug tops can take a 5-amp or 2-amp plug top, then each point becomes in effect a sub-distribution point.

I do not favour a complete ring in each room; it is preferable to break the ring on either side of the chimney. One circuit for each ordinary room fed through a 15-amp fuse or breaker from a central distribution point with an additional circuit for lighting on each floor, an additional circuit for a water heater, and a separate circuit for a cooker, would meet requirements.

I agree with the principle of fixing sockets in skirtings indicated in Section 5.0.1, but I am not sure that the means suggested by the authors are the best. A skirting front board, which could be cut to take sockets, could be easily and cheaply produced.

With regard to new insulating materials and cables referred to in Section 5.0.4, what are the potentialities of p.v.c. cables? Can they be made vermin proof? If they can, their use in prepared ducts will be a practical proposition.

On the whole, the suggestions made by the authors of Part 2 are in general outline similar to those sent forward from this area to the Installations Section Committee. The differences are mainly in detail.

Mr. J. H. Napper: There are three main points in favour of pre-fabricated houses. If 4 000 000 houses are to be built in the future, they must be planned properly as communities, they must be larger houses, and they must have better services. The paper mentions a floor area of 600–800 ft², but if we are to have better houses they must be bigger. Houses must also be provided at an economic rent, which affects the cost. In my opinion, these three aims can be attained only by means of pre-fabrication.

In regard to standardization and pre-fabrication there is much loose thinking. The paper makes an important suggestion in urging the need for collaboration between all those now engaged in this planning, but it does not go far enough. If the cost of a house is about £500 we shall spend £2 000 000 000 in 10 years, which calls for some sort of research beforehand. It would not be unreasonable to expect the Government to spend £10 000 000 for such research before the second phase of the housing programme starts.

Mr. R. W. Gregory: I like the simplified arrangement of the wiring installation suggested in Part 1. The proposal to use a ring main and 10-amp socket-outlets with plugs properly fused to protect the connected apparatus is sound, but I am not convinced that grip-joint light-gauge tubing is desirable for the system of wiring. The only advantage I can see in this method is that it is cheap.

No mention is made of the possible use of cable of the mineral-insulated, copper-clad type, at least for the ring mains and for the cooker unit. It is a safe system of wiring both electrically and mechanically; it is durable and can carry abnormal loads without danger either to its own insulation or to the structure. This makes it very desirable on all circuits where an increase in load is possible but difficult to assess at the time of installation.

The modern tendency in an architect-designed house is to reduce the need for portable furniture and to increase the use of fitments. The authors show this tendency in their design of a kitchen equipment in Fig. 1. Bedrooms and dining-rooms are planned in the architect's office. Cupboards, wardrobes, wash basins and bookcases are made part of the structure, and I think it reasonable to suggest that an architect who knows his job should have sufficient intelligence to fix the position of the necessary socket-outlets. There is no real need for the unlimited flexibility suggested by the authors. Although the authors suggest that outlet points are required every two or three feet round a living room, yet in the kitchen, where kettles, toasters, egg-beaters, washers and the many other gadgets displayed in the electricity showrooms are likely to be used, not an outlet is shown.

I am glad the authors refer to the possibility of using small circuit-breakers, instead of fuses, on the main distribution circuits. These breakers have many advantages, and I suggest that, if used on the combined intake and service panel shown in Fig. 1 instead of the local fuses, the consumers' main switch might reasonably be eliminated and the wiring on the panel greatly simplified.

To my mind, the coal fire is a desirable luxury in lounge or living-room during the winter, almost a necessity in the kitchen of a family house, but an unmitigated nuisance in every other room. This nuisance is aggravated when the rooms are small. Electric space heating should appeal to any ordinary householder's pocket when the cost of 100 kWh is the same, or does not seriously exceed, that of 1 cwt of solid fuel.

Mr. F. E. Heppenstall: There are two points with regard to wiring installations that require urgent attention, namely the standardization of plugs and sockets and the elimination of noise from tumbler switches.

I do not like the arrangement of the combined intake and service panel in Fig. 3 which shows the connections from the main taken direct on to the switch. In my opinion the mains should be taken direct to the fuses, so that the supply can be cut off from all the equipment, including switch and meters, using the simplest piece of apparatus available, namely the fuse cut-out. This arrangement would also protect against faults on the main switch, an important point which the authors' arrangement does not take into account.

It is not clear how the authors propose to connect the ring main. Is it to be connected with fuses at either end, or with just one set of fuses? Two sets of fuses, both of which would have to be removed to make the ring main dead, might cause some confusion and danger to amateur electricians.

The authors propose to use a main cartridge fuse apparently with fuse wire in the subsidiary fuses. They ignore the difficulty of getting discrimination between the two, forgetting that the cartridge fuse has a much shorter operating time. To get discrimination a cartridge fuse must have eight to ten times the current-carrying capacity of the wire fuse in series with it. If the lighting fuses are 5-amp, a 60-amp h.r.c. main fuse will be satisfactory, but where a power circuit with a 30-amp wire fuse is used a main cartridge fuse of about 240 amp rating would have to be adopted to get the necessary discrimination on faults. This is obviously out of the question. One type of fuse should be used throughout—cartridge fuses if they are necessary owing to the rupturing capacity of the system, otherwise wire fuses.

Mr. W. A. A. Burgess: I should like to take advantage of this opportunity seriously to ask our architects to get down to design. If they want any assistance in designing circuits and various services they have only to ask competent engineers to help them. It is incumbent upon the architect, as a professional man, to design for all services, electricity, water and gas. The present haphazard system of tucking water, gas and electricity services in available crevices in the structure cannot be too strongly condemned. An architect should be able to design channels running to the proper places, so that the services can be preformed and lifted into place quickly. I can visualize a system in which it would be possible for a tradesman to lift in pre-fabricated services at the rate of six houses per day.

I think the mineral-insulated, copper-clad type of cable mentioned by Mr. Gregory is one of the most flexible of systems for pre-fabrication.

It is probably far cheaper and equally efficient to provide a central refrigeration house and put in a cooled pipe in the correct place.

In my opinion the services should be brought in at the back of the house and not at the front. Why should we have to go into cupboards and under stairs to get access in the dark when a fuse needs renewal? The back of the house is where the majority of the load is and where it can be dealt with properly. The electrical service should be brought into a suitable alcove, accessible from outside for service adjustments and meter readings.

All fuses or other circuit-control devices must be guaranteed to carry their full rating continuously. My experience is that distribution fuses, in particular, are frequently installed which heat up long before the circuit is fully loaded and blow the fuses prematurely. I have had to refit completely two houses I have occupied for this reason. The true solution both for reliability and convenience is, I think, the circuit-breaker.

Mr. G. H. Hickling (*communicated*): To create a demand in the immediate post-war period for all the conveniences which electricity can provide in the home, the electrical industry must take

energetic steps to educate the public in what it can have: and this can surely best be achieved by equipping the new houses on what may now be regarded as a very lavish scale. I would commend all that is advocated in this direction in Part 2, whilst suggesting that adequate scope be allowed for providing many services not yet conceived.

Outlet-sockets and fuses should be designed for maximum convenience; a fuse at each socket would appear to be one ideal—perhaps a cheap, small, glass cartridge-fuse. Skirting mouldings might be designed with knockouts for the insertion of a socket unit at almost any point. If 10-amp plugs are standardized a special small type for clocks would be necessary.

Present meter boards are certainly a poor advertisement for the electrical services of the home. Why not provide an attractive central panel in a suitable part of the house, carrying the meter, main switches, fuses (or circuit breakers)—with a space for the gas meter as well?

The various "kitchen units" which have been designed appear excellent from the technician's viewpoint rather than from that of the user, for they all lack the essential requirements of convenience to use and adequate space. In this direction, I suggest standardizing suitable unit apparatus (including plain bench units) which could be fitted together as required. Coal fires must ultimately disappear—and with them the attendant complications in house construction—but their existence might be prolonged if a practical small automatic stove could be evolved having a convenience and efficiency approaching that of the power-house furnace.

[The authors' replies to this discussion will be found on pages 431 and 432.]

NORTH MIDLAND CENTRE, AT LEEDS, 23RD NOVEMBER, 1943

Mr. J. G. Craven: In Part 1 the authors have hit the nail fairly and squarely on the head in urging the adoption of a standard service and its mode of installation. This item is outside the control of the installation engineer or electrical contractor, and anyone connected with this section of the industry is very conscious of some bad examples of domestic services, as regards position, arrangement of meters, and a complete lack of neatness in the wiring between services cut-outs, meters, and consumers' main switches.

I can see no difficulty in standardizing service panels to meet all types of domestic loads and tariffs as shown in Fig. 3, but I strongly advise that if the supply authorities' fuse in the sealed chamber is to be of the h.r.c. type, then the circuits should be similarly protected, or circuit-breakers installed, as, owing to the discriminating qualities of the h.r.c. fuse, and its rapidity of action under fault conditions, a very high-capacity main fuse is necessary if the circuit fuses are to be of the re-wirable type. I believe a certain London supply authority which adopted the h.r.c. fuse some few years ago in their services found much trouble from stoppages of supply to domestic consumers, due to the inherent non-discriminating qualities of the re-wirable fuse.

I agree with Section 2 of Part 1 that it will not be possible to persuade Government planning departments or housing authorities to build all-electric houses in the strict sense of the word, but the first consideration should be to educate architects and house planners, and to allow as soon as possible a greater percentage of the total cost of the house for the electrical installation, so that the use of electricity can be expanded for domestic purposes. Parsimony with regard to domestic installations in the past, and the almost entire lack of facilities for extending them, except by the "twin-flexible type of amateur electrician," have definitely prevented the use of many domestic appliances in the small house under consideration.

From the figures given in Section 13 referring to the conventional and the new proposals, I calculate that the pre-war installation of twelve lighting points, five sockets, and the conduit for the cooker will cost about £10. Is this figure correct, as I cannot see how similar flats are to be wired taking into consideration the 20 per cent higher figure of £12 to cover 24 points, that is 12 lighting points, 12 plug points, the cooker and the water heater? The average length of run per point will of course be low, but this will not proportionately reduce the labour costs; there are constant items of expenditure whether the average run is long or short.

I like the arrangement of the kitchen equipment in Fig. 1, except that the food cupboard should be away from the water heater; unless the latter is very efficiently lagged, the cupboard will not be as cool as one would like for food storage. The foot space under the sink and cooker is excellent and of course essential.

The mention of pre-fabricated houses is particularly interesting. Do the authors visualize the electrical installation moulded into the house fabric at the factory, and then connected up by unskilled labour after the component parts are assembled on the building site? If plastic construction is feasible for the mass production of thousands of houses, then a moulded-in electrical installation is probably a practical commercial proposition.

In Section 4.3.4, do the authors mean a switch-socket and plug, or a socket and plug only? Whilst I agree that a 5-amp B.S. socket and plug will carry a current of 12–15 amp, the average switch combined in a 5-amp socket and plug will certainly not, and if 5-amp switch-sockets and plugs are used for 2-kW radiators taking 8–10 amp, trouble will probably be met with in switch failures. If the authors intend socket and plug outlets without switches, do they suggest that the plug will have to be removed to switch off the accessory connected, as it is a common practice with multi-element radiators for one element to be controlled by the switch-socket and plug to ensure that the flexible cannot be left live?

Will the authors explain what they mean in Section 5.0.6 by stating that "quick make and slow break" switches pay no regard to the essential qualities of alternating current? The only trouble I have experienced with this type of switch on alternating current has been entirely mechanical, usually due to broken springs.

Do the authors consider there is any possibility of fluorescent panels, mentioned in Section 5.0.7, being manufactured on the lines of Triplex glass with the fluorescent powder deposited between the laminations? I presume experiments have been made on these lines, but the area that could be illuminated by the ultra-violet light source might cause some difficulty. Also, does the u.v. radiation follow the inverse-square law, and is an anodized-aluminium reflector the best means of reflecting this type of radiation?

Colour is also mentioned in Section 5.0.7. I am sure the colour question will be very important in post-war housing. It is generally agreed that the 5ft fluorescent lamp, as we know it in this country, gives a very cold light, and I cannot see it being adopted after the war for domestic lighting purposes. I believe this type of lamp will be available in five different colours after the war with a length as low as 1 ft.

The colour of accessories is also important. The electrical manufacturers can take credit for having introduced quite pleasant colour schemes into their accessories, and electric fires and cookers.

Mr. A. Kelso: The universal sockets mentioned in Section 9 of the first paper, are to my mind, a step in the wrong direction.

By all means have fused plugs, but keep to an existing standard size.

Despite the good results of tests of 5-amp plugs reported in Section 4.3.4 of Part 2, where with 100 per cent overload the millivolt drop was about 30 as against 50 allowed in B.S. specifications for five types, I still think that the plug is not sufficient for the houses under review. There are hundreds of thousands of 15-amp plugs in use in this country; any change in size will lead to confusion. What is the advantage of the proposed 10-amp size over the existing 15-amp one? It might be slightly cheaper depending on the demand, but by using the 15-amp size the additional output would probably bring the price down to that of the 10 amp.

I hope a British Standard specification for flat-pin plugs will never be issued, especially for power and heating. Let us stick to the standards we have. After the last war the lack of standardization led to great inconvenience; the advent of British Standards helped to overcome it, although it naturally takes a long time for "odd" sizes to disappear. Interchangeability of components is at the moment under discussion between manufacturers and supply associations. All these have one point in common, namely standardization which will give obvious benefits to everyone.

Regarding grip-joint light-gauge conduit having an advantage over screwed conduit, my experience is that its only advantage is its quicker installation. I believe in making the earth conductor as reliable as the current-carrying parts, and as we usually make the conduit the earth conductor low resistance joints are necessary. Grip joints are usually satisfactory when installed, but in time the resistance increases more quickly than with other types.

Anent Section 15 of Part 1, the arrangement of the house service cut-out, meters, and the main switches, is generally an eyesore and by far the worst part of the electrical installation. In this area, the supply industry has approved a house-service unit incorporating those pieces of apparatus which will be adopted when normal times return. This unit is the result of a joint effort by engineers from many undertakings.

I suggest that h.r.c. fuses should be made for standard ratings of 5, 15, 30, 60 and 100 amp. The 5- or 15-amp sizes could be incorporated in the plugs.

The multipart-tariff prepayment meter can now be eliminated. I suggest that the fixed-charge portion of the two-part tariff could readily be collected with the usual house rent, and a straight prepayment meter used for collecting the unit charge. One undertaking with a large number of small domestic consumers collects not only this fixed charge, but also apparatus hire-charges and hire-purchase with the rent; the scheme is to be extended after the war.

While I favour a heavy main feeding a number of socket-outlets, I would rather see conductors run in conduit and passed through metal boxes where they could be bared and clamped, without cutting, to the terminals of a socket-outlet. In Fig. 3 the combined intake and service panel has circuit breakers as an alternative to circuit fuses. This has many points in its favour, but the breakers may be called upon to perform a very severe duty in the event of a fault in the wiring.

Mr. L. Raven: I feel that Part 1 is too pessimistic regarding electrical development and I should like to see a little more of the spirit of Part 2 incorporated in Part 1.

The tone of the first paragraph of Section 3 of Part 1 is too faint-hearted. The authors do not realize that emphasis has been put in this country on the use of current-using devices, because supply undertakings want to sell electricity. The small current-using devices have not needed much sales effort, and have been sold in large numbers. I seriously dispute the statement that any woman who has used an electric washing-machine would rather have it than a new cooker.

With regard to cooker wiring, I should like to emphasize the desirability of making adequate provision for supplying a cooker in every house after the war. If a suitable circuit is taken to the kitchen, it can be used for other purposes even if gas is used for cooking.

I support the continuance of one standard of plug and socket, the existing British Standard, and suggest that the present 15-amp socket should be used for all new points, appliances to be fitted with suitably-fused plug tops.

The grip-conduit system of wiring advocated by the authors of Part 1 certainly provides a cheap and efficient form of protection, but I am not at all happy about its use for earthing. All points that need earthing should be supplied with earth wires, and points that do not require earthing should not have earth connections of any kind.

Existing service connections have been criticized by one or two speakers. The usual untidiness at service points is not altogether the fault of the supply undertakings, and in recent months they have shown a very laudable desire to improve matters.

Part 2 answers some of the criticisms I have made of Part 1, particularly regarding the use of conduit. I hope the electrical industry will not take the title of Section 2 too literally and consider it represents *too distant* a future.

A word of warning should be given with regard to the kitchen layout in Fig. 1. The cooker needs to be easily removable for replacement, as it is the most abused of all electrical appliances, I do not like the position of the cold-water cistern over the cooker, and if we are to have planned kitchens the oven should be fixed at a higher level and fitted with a drop door.

Have the authors any further information on the possible production of small circuit breakers with adequate rupturing capacities to deal with the heavy faults likely under the conditions that will be created if electrical development proceeds on the lines they anticipate?

Mr. H. Moss: The electrical engineer cannot enter any of the new houses until they are built. Until some houses are built or specifications got out, I fail to see how any electrical man can design installations to be built into them. If there is going to be a considerable change from pre-war methods and materials which will warrant a redesigning of the electrical installations, then new methods may be adopted, but are they going to be immediate as the authors suggest? Personally, I cannot see that this will be so.

Although The Institution has issued wiring rules which have been accepted by many, others, including supply authorities, either ignore them and will allow anything to be put in, or they follow their own ideas. How will these rules function when many new ideas are introduced? It is time, in my opinion, for rules to be drawn up by the Wiring Regulations Committee of The Institution, for supply authorities, municipal authorities and companies, to accept them as a whole.

Mr. Craven raised a point of vital importance in asking whether the plugs or socket-outlets are switch-controlled, or are sockets and plugs only? I have tried for some years to arrive at a fool-proof installation, and I believe if it is to be realized the switch-controlled socket-outlet, preferably of the interlocking type, must be used.

I disagree on the adoption of a 10-amp plug. Some are still in use to-day that were installed thirty years ago, in spite of standardization. I think the standardized 15-amp and 5-amp sizes are sufficient for all domestic requirements. If we can afford to put a 10-amp plug in a house, we can afford to put in a 15-amp. There will not be much difference in cost.

I have always maintained that in small houses a very good and highly efficient installation can be obtained with light-gauge tubing and grip fittings. As to whether it should be a brazed or close-joint installation is a moot point. I know installations with close-joint tubing that have been in use for thirty years and are still giving very satisfactory service. I think we could omit the brazing, as this raises the cost of the tubing to that of heavy-gauge welded. Close-joint tubing can be made into a satisfactory job because when once installed it is permanent, it is secure and cannot, as a rule, be tampered with.

Dr. E. C. Walton: I agree with the authors that the present type of tumbler-switch was not designed primarily for a.c. work. The long break we get in that class of switch was intended for direct current. This long break is quite unnecessary if we consider the various types of thermostatic switch which operate quite satisfactorily. I am quite sure that suitable switches could be designed on these lines which would take up a lot less space than the present tumbler-switches.

I had hoped to hear something on single-pole fusing. What will happen if a neutral conductor, which is never precisely at earth potential, comes in contact with the "earthed" tubing? Much leakage will occur at that point.

In the kitchen diagram the water-heater should preferably be on the same side as the oven rather than on the refrigerator side.

No one has mentioned the difficulties associated with the barrel type of terminal fitted to most electrical accessories. It has to some extent disappeared, and it would be a good thing, in my opinion, if it were replaced altogether by a terminal of better design.

Mr. K. C. Coop: Regarding the suggestions that water heating in conjunction with boiler heating should be encouraged during the summer, and that the switches should be sealed off during the winter months, I feel that such obvious restrictions on consumers would not be welcomed and would not benefit the electrical industry as a whole.

In Section 3 of Part 2 are not the figures for power and heating at 1·5 watts/ft^3 and for lighting at 3 watts/ft^2 dangerous? Is it wise to generalize when, as regards room heating, there are such variable factors as exposure to the elements, type of building and method of heating? On this point, are we to assume that the present form of radiator with its very localized effect will not give place to new and improved methods of heating? As for lighting, it is not stated whether the figure of 3 watts/ft^2 refers to direct or indirect lighting, and no mention is made of the colour and surface texture of the surrounding walls. I should hesitate to give definite figures; each case should be treated on its own merits.

[The authors' replies to this discussion will be found on pages 431 and 432.]

SCOTTISH CENTRE, AT EDINBURGH, 12TH JANUARY, 1944

Mr. H. M. Speirs: With the possible building of four million houses in the next ten years some form of pre-fabrication for electrical installations seems called for, in preference to the type of installation indicated in the paper. I have worked out that, for the type of installation advocated, about 9 000 operatives would be required for ten years, i.e. about half of the available personnel in the contracting industry. This would cause a shortage of labour for many years to come, as existing houses have still to be dealt with, while works and other commercial buildings will require renewals and re-equipment. These facts should be kept in mind and some form of pre-fabrication adopted so as to reduce the demand on labour.

In Part 1, there are no details to act as a guide if the installations described are to be specified for houses in the immediate future. Cost figures are not directly indicated; the sum allowed for the installation as specified is apparently about £12, i.e. 9s. 2d. per point. As the cost of fitting an additional socket is stated at 6s., the allowance seems rather on the moderate side.

I do not agree that the relative costs with screwed conduit are unfavourable, when the additional supervision necessary for slip-joint conduit is taken into account. In Glasgow and Edinburgh the use of slip-joint conduit is not permitted. Casting concrete on to pre-erected conduit seems a retrograde step, because experience shows that interaction with the acid of the cement occurs, causing corrosion of the conduit and damaging the cable.

Socket-outlets in the ceiling suitable for lighting points do not seem advisable. Many years ago a similar system was adopted for office lighting, socket-outlets being provided round the picture moulding.

If the installation design under consideration has to be limited to small houses of four rooms as indicated in the paper, then pre-fabrication, making allowance for safety factors, should be adopted in some suitable form.

For lighting, the allowance of 3 watts/ft^2 seems more than adequate. For the average room, two 100-watt lamps should be sufficient and these might be permanently fixed in the form of semi-recessed lay-lights.

Moulding of conductors in the skirting boards is novel, but women might want to replace skirting boards by coves of the hospital pattern, when there would not be space at the back for conductors as envisaged by the authors.

I suggest that the authors consider the possibility of using mineral-insulated cable, which would provide adequate mechanical protection and also give good continuity for earth-return currents. If the houses were standardized, such cable could be made in pre-fabricated lengths with a plug at each end to engage the sockets in all switches and fittings. Pre-fabricated wiring of this type could be installed in about half the time taken for the conduit installation described. One socket-outlet per room might be provided, and additions could be made by pre-fabricated lengths of mineral-insulated cable laid in a suitable groove in the cove. At each socket-outlet position a single-pole circuit-breaker should be provided. I cannot agree that a non-controlled socket-outlet is satisfactory, as children insert hair-pins, etc., into the live sockets, often with disastrous results.

I favour the idea of a ring main, but feel that both ends of the ring should be brought back to the distribution board, and each controlled by a fuse or circuit-breaker.

The suggestion in Part 2 of distributed fuse protection does not seem advisable. Grouping of fuse protection facilitates fault location and is to be recommended.

The design of installations for larger houses can be left safely in the hands of consulting engineers and contractors, as the installations in such buildings have in the past been reasonably satisfactory.

The registration of operatives seems essential if the quality of electrical installation work has to be maintained. This, however, is a matter of policy.

Mr. P. d'E. Stowell: The main theme of both parts of this Paper is the laudable suggestion that a house should be erected as a functional entity having regard to the work which will be done in it. In this case, the facilities available are at least at important as the structure itself, and of all the services, adequate electrical facilities are most essential, electricity being the only service which can do practically everything. There seems to be every justification, therefore, for making the constructional features of the building subservient, where necessary, to the needs of these services, as is suggested in Part 2.

I am particularly interested in the improvement of service arrangements. In Edinburgh, we have already developed a neat and compact all-enclosed service arrangement for the larger consumers, and a number of these units are now installed. A corresponding unit for domestic purposes is very much to be desired, but would inevitably need mass-production methods and more standardization than can be achieved by a single undertaking.

The two Parts of the paper do not agree as to the number of outgoing circuits required. Is it really necessary to provide at least two lighting circuits in small houses, as suggested in Part 2?

Separate circuits are also suggested for the water-heater and cooker for which one circuit would appear quite adequate if the water-heater were installed close to the kitchen, as it should be to reduce heat losses from pipes where the consumption of hot water is greatest. In some areas, the water-heater and cooker are already interconnected, so that both cannot be used simultaneously; this has the merit of guaranteeing 100 per cent diversity.

Plug-in meters should be seriously considered, not only to facilitate installation and changing of meters, but also the testing of meters.

The 0·0225, 2-core service cable suggested in Part 1 has been standard in this city for some years, and is the only size of 2-core cable used for single-consumer premises. It has also been the practice of the electricity department to run rising mains in all blocks of flats.

Now that slow-break switches and even micro-gap switches are favoured for alternating current, could not a combined switch and socket be designed, in which the plug was turned through, say, a right angle after insertion to operate the switch?

Mr. J. F. Field: Regarding the advantages of light welded tubing with slip-on fittings, I should like to mention two recent experiences with screwed conduit. In the first, I was investigating the possibility of extending the wiring in my own home. The first piece of screwed conduit I found under the floor fitted very badly. The tube adjacent to a running coupling had no thread worth mentioning to hold the coupling in position, the thread probably having been stripped off by unskilled labour in screwing the ends. The earth continuity of the tubing was bound to be fortuitous, and supports the authors' contention that, on the average, light welded tubing with slip-on fittings gives better earth continuity tests than screwed conduit. On another occasion recently I noticed a wireman screwing the ends of some 1in conduit in a straight run, and was puzzled to know why the ends should have been re-screwed at all, since they already had an excellent thread cut on them by the manufacturer. The re-screwed ends looked very bright; examination showed that the threads had been almost completely stripped off. The diestock contained half a 1in die and half a ½in die. Judging from the first incident, it would seem that this is not uncommon. I believe the authors deplore the use of any conduit at all; I would like to see something more effective before agreeing, but I have little doubt that their preference for welded light tubing with slip-on fittings as against screwed conduit is sound.

In the busbar installation system, I agree that placing the fuse on the plug of the appliance is excellent and enables a standard size of plug to be adopted irrespective of the size of fuse required to protect the particular appliance. The lighting system for the small house of the future is on a separate circuit; this seems to be unnecessary. I suggest that the phase lead to each lighting point could be connected from the nearest point on the busbar direct to the lighting switch, a cartridge fuse being inserted above each lighting switch. This arrangement would ensure that any fault on the main busbar system plus the phase leads to the individual lighting switches would be cleared by the main fuses for the house, and that any fault on the lighting switch or on the lighting circuit beyond it would be cleared by the individual cartridge fuse above each lighting switch. In effect, this method amounts to the same thing as putting a properly-graded fuse in the plug of each appliance. A lighting fuse failure would then be very easy to locate.

The suggestion that the existing 5-amp B.S.I. plug should be up-rated to 10 amp appears to be excellent, and I suggest it might even be up-rated to 11 amp, thus covering a 2½-kW fire at 230 volts.

Mr. W. Duncan: Shortly after the last war, when large-scale provision of working-class houses was undertaken by municipalities, installations were provided for lighting purposes only. Since then, owing to pressure from various sources, the position has been slightly improved. In this city, two socket-outlets are allowed, one in the living-room and the other in the bedroom, which has no other means of heating. One light only is permitted in each room, so that the complete installation in a four-room house consists of seven lighting points and two socket-outlets. In 1938, the cost of the electrical installation in this size of house was about 1½% of the total cost of the house. If this figure could be increased a much better installation could be provided, but with building costs as they are, every possible economy will be exercised and this will not be confined to the electrical installation only.

I do not think that the introduction of the proposed new universal socket is necessary. In the paper, it is admitted that only one point is required in each room for heating purposes, and that there is no difficulty in deciding on the position. If this is so, why should we not retain the present 15-amp, 3-pin socket for the heating point and install the present standard 5-amp, 3-pin socket for all the other points in the room? The 5-amp socket-outlets will be suitable for any appliances except the fire, and the 15-amp socket-outlet will permit the consumer to use any size of fire that is desired. In this area, we have connected just over 60 000 new domestic consumers in the last twelve years, and the socket-outlets installed have all been of standard 5-amp and 15-amp, 3-pin types. The introduction of still another standard socket-outlet, as suggested, will only increase the annoyance and confusion already caused by the use of different sizes of sockets just at the time when we are beginning to benefit by the changes which have been made.

Rising mains in flats should be provided by the supply undertaking. A consumer in a suburban area is generally provided with a free service cable up to a certain length, and it is surely illogical that the same facility should be denied to another consumer simply because his "house" happens to be built over another one.

The provision of conductors behind room skirtings which can be tapped at any point seems to be met by the use of mineral-insulated cable, which is smaller in diameter than a pipe containing cables of similar capacity and can be recessed into the straps to which the skirting board is fixed. If builders and architects would arrange for fixing skirting boards with screw nails instead of driving nails as at present, this small detail would be of great advantage from the installation standpoint and also when extensions or repairs were carried out later.

Mr. A. F. Stevenson: I had hoped for a more revolutionary paper, as I think that wiring has stagnated. The single-pole switch is dangerous as it is very often on the neutral wire; this has caused fatal accidents. Double-pole switches would prevent this and enable alterations and extensions to be made much more readily. I favour the ring main.

Mr. D. W. Low: In Part 1 I do not agree with the statement that a solid fuel system combined with an immersion heater is probably the ideal system. The fitting of an immersion heater in an existing house is admissible. But in the new houses, the proper type of heater is one designed from the electrical and

installation point of view with a connection suitable for piping to the coal fire boiler, if desired. The size of heater that should be fitted into the new houses is one with a capacity of not less than 20 gallons; the loading does not need to exceed 3 kW.

The authors suggest that to reduce the peak in the winter months the switch should be sealed against use. My view is that after the war to keep water heating off the peak, ripple control will become universal. There are several systems of ripple control, one of which has been used very successfully in Yorkshire. It has the advantage of being selective—at a peak load a signal is given and cuts out the water heaters which are up to temperature. If the cutting-out of the heaters is not sufficient to bring the load down, another signal goes out and so on until all the heaters are cut off.

[The authors' replies to this discussion will be found on pages 431 and 432.]

SHEFFIELD SUB-CENTRE, 19TH JANUARY, 1944

Mr. H. Wheeler: As a member of the Electrical Contractors' Association, I am very interested in post-war planning. Part 1 of the paper is very modest, yet if 10-amp plugs are made standard for all purposes, what will happen to the millions of 15-amp sockets in use in this country, carrying as they do, the sanction of the B.S.I.? The ring main is a very sound argument properly applied, but when the authors suggest wiring for, and completing, 12 lights, 12 socket-outlets and conduit for cooker and water heater, at a cost of £10–12, their figures appear to have become rather mixed. I do not agree with flexing-out.

Part 2 suggests that a house should be built round its requirements. This is very good in theory, but has many pitfalls in practice.

The scarcity of rubber is likely to be acute for some considerable time, and anticipating this, the C.M.A. has introduced a substitute, polyvinyl chloride thermoplastic compound, costing 30–50% more than the material it replaces.

The plastic skirting board with hidden conductors does not remove my difficulty. I am looking for a means of connection that will obviate the necessity of crawling on hands and knees, only to find that the furniture has been moved and all outlets have been covered up.

Mr. W. G. Davies: First, I should like to thank you for your kind invitation to be present at this meeting which in dealing with post-war housing is a matter of profound interest to me. As City Architect of Sheffield, I shall be responsible for a large post-war housing programme of at least 20 000 houses, and for this reason, the paper is of considerable value and interest.

At the end of the paper, there are some candid remarks, indicating that the ordinary architect is not sufficiently advanced in electrical technique to produce the necessary designs. I agree with this; my remedy is to obtain the advice of a specialist. The post-war building programme will give work to every section of the building industry, with a wide scope for improved methods of design and operation, and the utilization of the new materials to be developed after the war. I understand the electrical industry is the youngest body connected with building, and that there has been more progress and improvement in this industry than in any other section.

Reading this paper, however, it is quite evident there are ample fields for further improvement. Some of the suggestions appear rather fantastic to-day, but these advanced views are just those which must be considered for the future. The outstanding item which appeals to me is the suggested standardization of details of fittings and equipment; this must mean economy, safety, and greater facilities for the users of this equipment. Standardization of electrical components appears to be a real necessity, for there must be hundreds of types of plugs, switches, wiring, etc., in use.

Another point requiring attention is the layout of such installations. This should provide for the maximum amount of electrical equipment likely to be embodied in a house, so as to avoid the difficulties arising when additional fittings are required, possibly in a short period after the house has been erected, such as a heater or cooker. Is the ring-main system the solution to these difficulties, and will it offer economies in the provision of additional fittings?

All these problems will have to be dealt with in post-war houses which may be constructed of pre-fabricated units, possibly with new materials, the complications in the use of which are difficult to define at present. It is evident that there will have to be a complete revision of all the old ideas.

One other suggestion—it is evident that collaboration is required between all interested industries, with meetings to discuss the various matters of mutual interest, the results being embodied in plans and specifications.

Mr. A. Haddock: I agree with the authors' suggestion that the appearance and location of house service equipment must be improved. I disagree with the proposals to combine supply authority's and consumer's equipment. Installations never reach finality, so that changes are inevitable and even desirable. It is most undesirable that, when the consumer wishes to alter his installation, he should be involved in the possible replacement of the supply authority's house service equipment as well. I welcome the suggestion that a main switch should be provided by the supply authority. Sheffield has always done so.

I consider it better to bring the incoming service cable first to the fuse or cut-out, rather than to the switch. The switch requires most attention, and it is an advantage if a maintenance man servicing a faulty switch can make the switch dead by withdrawing the fuse.

The authors refer to the likelihood of more multi-tariff prepayment meters being used. These meters usually collect the fixed charge by means of an electrically-driven continuously-running clock. With the combined unit designed by the authors, the meter can be made dead by opening the switch, thus stopping collection of the fixed charge during periods when the supply is not used. Sheffield has used these meters to collect arrears, and has developed a design of service unit to overcome this difficulty. I prefer that the unit should be made of metal, as plastic compositions are not yet strong enough to withstand the ill-treatment to which the unit is exposed.

Sheffield has evolved a combined cable-sealing end, main fuse, and main switch in cast iron. The connections are: (1) service cable to fuse, (2) fuse, underneath the switch, to meter, (3) meter to switch, and (4) switch to consumer's distribution board. The wiring to the distribution board leaves the unit at either side near the top, either through a bushed hole or by a direct conduit connection. The meter fits close to the top of the unit, and the connections are covered by a shroud which is a part of the unit. There are no exposed connections.

I doubt the advisability of up-rating the 5-amp plug to 10-amp, and prefer a standard 15-amp socket with fused plug heads.

Mrs. C. J. Keep: As Chairman of the Sheffield Branch of the Electrical Association for Women, I am very grateful for the opportunity of taking part in this discussion concerning the post-war planning of houses from a woman's point of view.

It is disappointing that the paper does not provide for an all-electric house. The E.A.W. make it one of their slogans, and the young women now using up-to-date electrical apparatus in

factories have a right to expect modern electrical equipment in their houses after the war. Can it not be produced just as economically as putting in expensive fire-places and cookers?

Plugs are a very controversial point. It is ridiculous to have all the plugs on the skirting board, and I disagree with the authors' suggestion that the plugs should not be fused. I think it would be much safer to have plugs fused. They should also be of the interlocking type.

An important and essential need for cooking is a quicker boiling ring. Some manufacturers provide one, but only one per stove. In the Bradford engineers' planned kitchen, the hot-plates and grill are separate from the oven. This seems to be an excellent idea. I would also suggest more boiling rings, perhaps smaller in size, but of high power. A large number of people consider electric heating and cooking too slow. I think all cookers should be thermostatically controlled.

After the war, we are going to be concerned with homes, and I hope families, with adequate kitchen arrangements and sufficient space for a refrigerator and a washer. It does not matter if these are standardized. I think most electrical equipment could be simplified and made more fool-proof. The average person does not seem at present to be really electrically-minded. Cut-out devices should be used on all equipment wherever possible.

I must postulate that the standard cooker, washer and refrigerator be supplied at very low prices. This is absolutely essential for working-class women, and I do ask you all to use your influence to bring these essentials within the reach of the lower incomes.

Mr. G. W. Randell: The desire to cheapen installation work is readily appreciated, and any electrical work required in the household in planning for the future, if regarded as a real necessity, should, as such, command a good price. However simple the wiring may be, simplicity would certainly tend to speed up the installation and thereby cheapen it; but at the same time, there is a serious risk that the work will be carried out by anyone without regard to good workmanship. This is the all-important factor in any installation work, and unless attention is directed to it, the industry will drop to a low level, and we shall find a plumber and gas fitter established as a "plumbtrician."

Another important point to be considered is in connection with the training of youths; with the simplification of wiring, interest flags because craftsmanship is eliminated.

Mr. H. Riley: There is one point I should like to touch upon, which no one has mentioned. The technical committee, advising the Board of Trade and other Government Departments, has put forward some very good suggestions. It suggests built-in refrigerators and cookers for 4 million houses, at a very low price. How would these be distributed and to what class of house, and who would service them? The general impression is that the contractor and distributor will both be cut out, and the contractor, who did not supply the item, will not service it. The built-in refrigerator or cooker is the most difficult of all to service, and I am anxious to find out what the authors have decided will be the outcome of this particular problem. The Electrical Contractors' Association, with a market of 4 million of each item, possibly totalling some £98 million in value, and distribution opportunities taken from them, will want to know who is going to pay, if called upon to service these components.

My other point is on the question of sockets. The Technical Committee will probably recommend a flat-pin plug. Some circles believe that there will then be a very grave danger that American- and German-sponsored firms, who already use flat-pin plugs and sockets, will try to dump their surplus products in this country.

The average person, being unable to get service at night, replaces fuses with any fuse wire, and so allows the value of the fuse to disappear overnight.

Mr. R. H. Coates: In Part 2, the authors state that the casing and capping systems had been superseded by the end of the last war. At the discussion on the paper in London, speakers criticized the specially-designed skirtings of Fig. 2 as a return to this outmoded form of installation. In Sheffield casing and capping has remained in use up to the present time. This supply undertaking has quite a large installation section, and in view of the authors' opinions, I have discussed the matter with our installation foremen, who combine 160 years of experience and have wired 28 000 estate houses and 60 000 slot-meter installations, as well as other premises. Their opinion is that provided the houses are built of brick and wood joists, casing and capping is the best method available, while for houses built of concrete, steel conduit is preferred.

It seems of particular significance to me that these men have on occasion to repair faults, not only on their own installations, but also on work by other contractors. They have had very much less trouble and repair work with casing and capping than with other methods, and in one particular job, originally installed in screwed steel tubing, the conditions were such that it quickly corroded and had to be replaced by casing and capping painted with white lead and varnished.

The annual reports of the Home Office on "Electrical Accidents and their Causes" call attention to leakage currents and the unfortunate results when the metal earth circuit is discontinuous or of high resistance. They indicate that a metal-clad job is very dangerous unless it is not only installed correctly, but also periodically checked for earth discontinuity.

A large supply undertaking includes, in its normal day-to-day activities, the clearing of faults on domestic premises and the checking and approving of installations before connection; it is therefore in an unrivalled position to weigh up the merits of the different types of installation. We operate an inspection department entirely separate from our installation department, so that we are able find fault with our own work.

Mr. J. W. Taylor: As an installation inspector of the Sheffield Corporation, my duties cover all installations irrespective of who has wired them. I would be prepared to vouch for the advantages of capping and casing, as against conduit, etc. Where alterations are made in house installations which have existed for some years, my own experience of v.i.r. is that the state of preservation in capping and casing has been extremely good, even after 30 years; the same cannot be said for conduit.

I have inspected many buildings after a fire and cannot recall one instance where I could definitely place the blame on the capping and casing system. But with conduit and lead-covered cable I have found that broken continuity, faulty earthing and contact with gas piping are only a few of the potential fire risks. I suggest the authors include fire-proofing for all flexes.

I feel some advance could be made if we forget the fuse, as we know it at present, and use something on the lines of a current limiter which could be reset by the consumer. I am drawn to this view by the current I.E.E. ruling of placing a fuse in the live wire only, for I feel the public are intelligent enough to withdraw the faulty apparatus and make a readjustment, thereby saving themselves and the department a lot of inconvenience. This arrangement was adopted some years ago in a Sheffield hospital and has proved successful.

In view of the quality of labour employed, what would happen to this system with the present lax methods allowed in the contracting industry? I think that before any new ideas are considered, it should be compulsory for certified operatives and contractors only to do installation work.

[The authors' replies to this discussion will be found on pages 431 and 432.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 23RD JANUARY, 1944

Mr. C. J. O. Garrard: Agreement on methods of wiring houses pre-supposes agreement on the methods of heating to be employed. All-electric water and space heating is for a long time likely to be too expensive for the class of house the authors have in mind; also on a broader view it is wasteful of energy owing to cooling-water losses. The base of the domestic heating load should, I feel, be covered by the combustion of solid fuel, e.g. coal, or preferably briquetted coke, or gas, which should be a plentiful by-product of the efficient utilization of coal. The coal should be burnt in a boiler supplying hot water and central heating to the house; electricity should be used as a boost for either or both of these purposes.

A suitable central-heating installation for a new 5-room house should not cost more than £40 including erection, assuming mass production of the apparatus; the cost in 1934 of a similar installation was £45. A comparison of running charges shows that a central-heating system is not more expensive than the conventional methods of heating a small house. Its adoption would remove the necessity of allowing for such heavy electrical loads as the authors mention. Their statement about water heating lends support, I think, to my experience as to the economy of central heating.

I agree with the authors on the relative values of a refrigerator and a washing machine; why do they show a refrigerator in Fig. 1, Part 2, but no washing machine? The one-piece kitchen fitting shown I regard with misgivings. It would be expensive (about £75), awkward to accommodate and in its remoter recesses impossible to keep clean. It should be replaced by standard units, e.g. sink, cooker, washing machine, cupboards, etc.

With regard to design details of the components, the taps are too low; the cooker switches and if practicable the oven itself should be higher, and there should be one or two socket-outlets.

The 15-amp 2- or 3-pin plug could be used universally; it would have a better cord-grip than smaller sizes. The suggestion of a continuous busbar round each room seems too liberal. A socket in each corner of each room would be enough; one should always be provided on the stairs for a vacuum cleaner.

I agree that two or three automatic circuit-breakers would be preferable to the usual bank of fuses.

The suggested lighting load of 3 watts/ft² would give a loading of 432 watts in a room 12 ft by 12 ft. This is about double that required with efficient fittings.

Mr. A. J. Heelis: The Coventry undertaking has recently been equipping and wiring two experimental houses and in this connection has investigated the ring-main and the room-circuit systems of wiring. By "room circuit" is meant the running of one 15-amp circuit to each room to supply any number of socket-outlets on the assumption that the maximum load would never, under normal conditions, exceed 15-amp. A detailed comparison showed very little difference in the cost of the two systems.

The room-circuit system was adopted because it offered advantages over the ring-main. 15-amp socket-outlets were installed throughout, approximately three to each room. The uprating of the 5-amp socket-outlet to 10 amp, which has been advocated, was carefully considered, but it was decided that this would be a retrograde step in view of the trouble experienced in the undertaking's area of supply, where 2-kW fires have been used on the 5-amp type. I believe that if the 15-amp B.S. 3-pin were adopted as the standard socket-outlet, the reduction in price which would follow, would remove the need for uprating or for new types.

The periodical inspection of installations in public buildings indicates that grip-joint conduit is not nearly so good as screwed. Owing to finding poor electrical continuity in schools wired with this system, we decided some 10 years ago to go over to screwed conduit in future installations. Screwed conduit was used in the two experimental houses, for as they were of sectional steel-framed construction a conduit system of reliable electrical continuity was essential.

The service unit, designed by the Coventry undertaking, is wired differently from that shown in the paper, for where meters of the two-part tariff prepayment type are installed no provision can be made for the consumer to switch off the supply to the meter.

The space provided for the meter by the authors would not accommodate all types of meters, and I think the service unit should be confined to the supply cut-outs, switches and consumers' fuses, space being provided at the top for easy fixing of various types of meters.

(Communicated): I think that the 15-amp protection, as suggested in the room-circuit system, would provide a very reasonable degree of protection for small domestic appliances, and 15-amp B.S. fused plugs could be recommended as optional. This is preferable to the ring-main system, where fused plugs, as suggested in the paper, would be essential and would be a source of danger if misused, as they probably would be in many cases.

Mr. G. M. Stephens: I strongly support the suggestion of a universal plug and socket, but there is one point about which we cannot be too careful. Premature introduction would probably force a decision at the present time in favour of the 3-pin type, whereas with the future development of plastics a 2-pin plug might be found better. With no metal round a room a 2-pin socket has advantages. In the interests of safety, a non-reversible 2-pin plug should be developed. Many fatalities have been caused by reversible 2-pin apparatus.

In Section 14, Part 1, the authors advocate the use of a batten lampholder, or some other fitting, from which the flexible could be taken by means of a plug. Fatalities can happen with this type of fitting, because the flexible cord is taken to a piece of apparatus incorporating a single-pole switch. By simply inserting the lampholder adaptor the switch on the apparatus can be put in the neutral wire; this offers no protection when a fault occurs.

The kitchen arrangement shown is compact, but of necessity the daylight conditions would be very poor, because the window would have to be either to the left, right, or behind, whereas housewives like to have the light in front of them right on the job they are doing.

In Section 4.3.4 of Part 2, 15-amp fuses are suggested for ring-main control. The figure seems to be a little low, because on a demand of 7–8 kW there would be little margin for extra heat. I think the figure 15 has been proposed to keep the protection low, thus limiting the load which may reasonably be expected.

Mr. G. A. P. Jewiss: I agree with Mr. Garrard on unit furniture, and although I like the layout of the kitchen illustrated, I feel that it would be improved if it were designed on the unit principle with the kitchen oven a little higher. The clock shown could be fitted with a time-switch for the oven. The broom cupboard should have a fan-heater element for drying clothes in wet weather.

In planning the future house, the heavy-current wiring should be concentrated in the kitchen and bathroom area. If kitchen and bathroom equipment could be manufactured complete in the factory, the house could be designed to take these units one above each other in a two-storey house, or the bathroom arranged to back on to the kitchen in the flat or bungalow; with this arrangement all necessary wiring, hot- and cold-water pipework, etc., would be very short, and could be made accessible by removable panels.

If the units were factory produced, the cost would no doubt be very much less than the kitchen arrangement shown. Unsightly pipework on the walls of the kitchen would also be eliminated. More power-plug points could be provided in the living-rooms, and need not necessarily be connected to a ring main.

The combined intake assumes that there would be only one meter; if the installation were used for lighting only, probably some financial adjustment could be made. This combined service panel could be situated near the kitchen intake giving even a shorter run of wiring to the domestic apparatus.

With regard to conduit, I feel that the progress made with plastics might eliminate the screwed-conduit system, which seems to be unnecessarily bulky for domestic premises. In fact, I prefer a completely-insulated plastic enclosure for domestic apparatus, particularly on bathroom equipment.

The mercury fuse was developed and satisfactorily tested many years ago, up to, I believe, about 10 amp. It consisted of a column of mercury in a glass tube which was separated by pinch effect when the current exceeded a predetermined value. The fuse was easily re-made by tilting the tube. Has the author heard of it, and is there any reason why it should not be used for domestic installations?

Mr. P. W. Keeley: What is the cost of the revolutionary electrical-installation work covered in the paper? In the past, the average electrical installation of houses up to about £1 500 was about 1½% of the cost of the house. The minimum should be about 3–3½% of the cost of the house. But before the fitments described can be put in, we must ask ourselves if the buyer can afford them and if the architects will make the necessary allocation in their prime cost. My experience has been that architects do not, and several architects I have spoken to do not like the question raised at all. The usual way an architect plans a house is to take the price the client is prepared to pay and work out his bill of quantities on this, including everything except the electrical installation. This is quite wrong; the amount of electrical accessories to be put into a house should bear a definite relation to the cost of the house and must be such that the person who is to live in the house can afford to maintain.

Mr. S. Shaw: It is becoming the custom to install space-heating units in fixed positions, with permanent connections which could be made from the ring main, instead of to socket-outlet connections.

The authors rightly refer to the decided advantages which electricity has in connection with the small labour-saving units, many of which are required at table height. I suggest that instead of putting the ring main at skirting level, as proposed, it should be about 3 ft above floor level and be incorporated in future in the structure of the building. That would shorten flexible conductors, prevent their wear through rubbing on floors and against furniture, and give other advantages.

I am surprised that the authors suggest connecting the cooker and water-heater to the same circuit. These two pieces of apparatus are in daily use, during certain parts of the year at any rate, and in the event of a major fault developing and clearing the protection for that circuit, the housewife is temporarily deprived of two very essential services. Experience indicates that the cooker and water-heater should be separately protected.

The service layout is definitely an advance, but a note of warning must be sounded. A compact unit may be crammed into too little space, which may be very desirable from some points of view; but these units have to be maintained, and to make replacements and repairs the necessary space for a man to work in safely must be provided.

A previous speaker has referred to the desirability of obtaining earth-free situations. In domestic premises that is a very important point. The recommendations do not refer in detail to the vexed question of earthing portable apparatus, but if plastics can be developed to incorporate circuits and the manufacturers can provide protection for current-carrying devices by means of plastic cases, we shall have no earthed paths to cause fatalities.

Dr. W. Wilson: The blessing which the authors have given to grip conduit is, in my opinion, unfortunate; I consider its use to be definitely unsafe. For simple runs over a flat surface it is no doubt fairly reliable; but in domestic wiring, especially for existing houses, there are apt to be positions where the insecure grip-type joint is inadequate. A case in point is the short horizontal tube run under the floor-boards between a light in the ceiling below and the riser from the switch by the wall. A time is sure to come when this tube is cut too short, when the wireman will force the riser away from the wall and spring it into engagement with the elbow. By forcibly screwing down the collar he will make the joint hold for the time being; but the vibration of passing traffic will probably make it part and later the gaping edges will saw through the insulation of the taut cables. I am certain that a really positive joint, as given by screwed conduit, is essential for permanent reliability.

Mr. H. F. Marshall: I would like to bear out Dr. Wilson's remarks about grip conduit. The great trouble in the electrical installation industry is that anyone can set up as an electrical contractor. The authors seem to forget that such people, and their nondescript employees, have carried out a great deal of domestic installation work, and will, I expect, do so in the future, until such time as all operatives are compelled to register as efficient wiremen. I would not dare let wiremen of this sort work on grip conduit, nor on any other system. Most of the faults on domestic wiring I have had to deal with have been on grip conduit installations wired by such people. It can be done properly and makes quite a good job, but it must be done carefully by a good wireman.

Mr. Rawll said that the Regulations are too onerous. I do not agree, mainly owing to the type of labour often employed for this work. Cheap wiring used to be advertised at 7s. 6d. per point—I could not buy my materials at that price, much less pay agreed rates for labour.

It has been said that fused plugs are unnecessary. A standard 10–15 amp plug must be fused somewhere for small-current apparatus, and therefore I think a fused plug is necessary.

To standardize on 3-pin 15-amp sockets, using the earth only when desirable, is a sensible idea. If the third pin is earthed in an earth-free situation, such as a bedroom, an element of danger is being introduced.

A service panel on the lines suggested would be a great improvement. At present, the connections between service mains and consumers' main switchgear are frequently an eyesore, and since there is usually a quantity of unprotected v.i.r. cable at this point, there is also some danger.

With regard to allowing 3 watts/ft^2 for lighting, it seems to me that allowing for recent developments in lamps, the total lighting load in this class of house will at any moment rarely exceed say, 230 watts, or 1 amp; we can safely ignore this as a load. But we should now be thinking in terms of light output, or lumens/ft^2, rather than of watts required.

Mr. P. A. Ottmann: I am surprised that the authors of Part 1 should have based their design of the electrical installations desirable in the post-war house on the standard materials available pre-war. Vast strides have been made in plastics since then and if it were not for hostilities we should now be employing some of the extensive improvements already made. It is, however, gratifying that in Part 2 the authors visualize the great possibilities of plastics for electrical installations in buildings.

With the appearance of pre-fabricated interiors for houses, it

seems very opportune to break away from the old traditional wiring system of rubber-insulated cables run in conduit and to install on the lines suggested in Part 2.

With regard to the ring-main system, although it tends to reduce the overall dimensions of distribution boards, if only three fused circuits are provided, as suggested by the authors of Part 1, I consider the distribution boards should provide fusing for: (*a*) at least two lighting circuits, except in one- or two-roomed dwellings (15-amp capacity); (*b*) a separate circuit for all socket-outlets provided in each room, except in small-roomed dwellings where one circuit for two rooms could be installed (15-amp capacity); (*c*) a cooker (30/60-amp capacity), and (*d*) a water-heater (30-amp capacity). The suggested circuits for socket-outlets would eliminate the possibility of all socket-outlets on the ring-main system being out of commission due to an open circuit.

I agree with the authors' suggestion that 10-amp socket outlets should be standardized and used for both lighting and power circuits.

Mr. G. Grainger: First we must lay down general principles which provide for: (1) adequate service; (2) new methods based on experience, to cope with all-round post-war demands covering materials and labour in the most suitable and economic form; (3) maintenance of quality consistent with reasonable costs, and, (4) control of some kind to safeguard against past inefficient and dangerous practices.

Arguments for and against the different wiring systems can be endless. I suggest that some of the faults referred to are not so much a condemnation of the system as that of the craft of installation. Inefficient screwed joints are frequently found; while damaged or overset adjustable dies, or careless screwing, can ruin the very best conduits. We should always aim at the highest standard of workmanship.

I suggest that it is not economical to ring each room completely in a 4- to 6-roomed house. Apart from cable quantities, there is the extra work entailed by doorways, built-in cupboards, etc. In 1922 the vexed question of costs in the controversy between gas and electricity caused one large building estate in North Lancashire to reject electric lighting. I tried to see what could be done in the way of a sound electrical installation at a competitive cost, and eventually submitted, as a Student Member of The Institution, a paper outlining the use of what I then referred to as a "socket feeder circuit" for supplying socket points throughout the house, and where possible arranging these back-to-back for adjacent rooms. This circuit used the minimum amount of cable, but could not be regarded as a true ring main. A lighting system using ceiling switches only was also included; the economy will be readily appreciated, there were no switch drops, and the floor and ceiling wiring could generally be arranged to make a further saving in materials.

With regard to plug and socket standardization, we should use the physical dimensions of the 15-amp size as a basis for the design of: (*a*) a non-fused 15-amp size for use in a composite unit incorporating separate local fuses; (*b*) a unit as in (*a*) but for use as a single unit with the central system of fuse or circuit-breaker distribution, and (*c*) fused plugs for 10, 5 and 2 amp. For the present purpose, these could all be of the non-switched shutter-type socket, with liberal looping-in accommodation.

It is regrettable that "flexing out" has been mentioned, as I think that to-day there must be thousands of cases where the fire and shock risk is very high, due to the promiscuous and indiscriminate use of flex.

With regard to the service panel, I favour the use of small circuit-breakers in place of fuses.

Mr. D. Kingsbury: I cannot condemn too strongly the kitchen equipment shown in Fig. 1 of Part 2. As four million houses are to be built as soon as possible after the war, it behoves us to go to a considerable amount of trouble immediately in making experiments and doing research to assure the maximum comfort and labour-saving devices for these new houses. Every mistake now made may be repeated four million times if the anticipated rapid progress in house building is achieved. If the need for building were less urgent, we could rely more on slow evolution in attaining good design. The kitchen equipment shown is exactly what one would expect on giving a draughtsman a list of things to be incorporated and leaving it to him to make a tidy drawing. As far as I can see it bears no relation to the household needs of the average British artisan family.

In this equipment, all the work is done in what amounts to a hole in the wall, instead of at a table or bench with a window or some sort of outdoor view. One sink only is shown, whereas I am quite sure that two sinks, one for washing and one for rinsing, and adequate draining racks would do more to lighten the work of a housewife than any other single development in the domestic quarters. A refrigerator is shown, but the general type of person to occupy a house of this size has neither the money nor the foresight to buy foodstuffs sufficiently far in advance to need a refrigerator; there are so many things more needful.

The taps over the sink are very awkward for filling a large saucepan or a bucket with water. The oven is far too low; 27 in from the floor to the lowest groove is about correct. It would be interesting to know where the light is coming from for the various holes marked "Cupboard," "Refuse bin," etc. I think that the lighting trough and ventilation grille, and other cavities in the upper part of the equipment, since they are over the stove and over another point where the water may be hot enough to give off much vapour, will take as much time to keep clean and sweet as a whole host of reasonably-disposed kitchen furniture.

Many responsible engineers have had to help in their own homes in the past few years, and it would be no small gain if the experience so gathered were reflected in the future layout of kitchen equipment. From my limited experience, I suggest that good engineers, as distinct from draughtsmen, should be entrusted with this layout work, and should work as housewives and nothing else for a year or so, during which time they should be allowed to have any desirable arrangement installed, with as many changes as may be necessary, in order to arrive at simple, workable, labour-saving schemes.

It seems common sense to me for space heating and bulk water heating for all normal occasions in the small house of the future to be carried out with coke fires with built-in lighting arrangements. We are a long way from the era when we can dispense with non-electric forms of main heating, and yet retain sufficient ventilating, drying and airing facilities to remain healthy.

Mr. J. L. Ferns (*communicated*): Attention should be drawn to the logic of plug capacities. Most fires in use are of the 3-kW size. It is clear that the average consumer is liable to draw approximately 15 amp from any heating plug in his house. He must therefore be equipped with plugs of 15-amp capacity. If the plug proposed by the authors will carry 15 amp then it should be rated as such and there will be no argument, but if its rating is really only 10 amp then it is obviously useless for its duty, and no qualified engineer dare risk installing it. It must be remembered that a house is built and equipped without any foreknowledge of the apparatus likely to be used by the incoming tenants.

As regards the ring-main idea, the elementary rules regarding the division of current along parallel paths must be recalled. It is quite easy to foresee conditions under which the ring main will not function as the authors suggest. A great deal depends on

the situation of the service in respect to the points liable to receive maximum simultaneous use. If this electrical difficulty is to be overcome a most complicated clause might have to be added to the I.E.E. Wiring Regulations.

A great many of the authors' difficulties would be overcome if they could obtain an alteration of service practice, which is probably more important than the special unit they have proposed, namely that the supply undertaking's service shall be situated as near as practicable to the load centre of the building. The extra cost would be borne by the consumer, of course, no matter what the immediate arrangement might be. At the present time a mains engineer has to terminate the service cable as soon as possible after entering a consumer's premises. Consequently, there has been a tendency for wiring contractors to bring all circuits back to a point which may be most unsuitable from the electrical point of view. This tendency is also aided by the need for studying the consumer's freedom to choose either a flat-rate or a two-part tariff. If the service could be placed near the load centre of the house there would be little need for the ring main, because of the shortening of the wiring runs. If the Wiring Regulations were also relaxed to allow a bedroom or stairway plug to be coupled with a downstairs plug on one circuit (or other reasonable allowance for diversity of plug usage), this would provide all the alleviation which could be expected from the Wiring Regulations Committee; yet this proposal could give considerable further economies which would outweigh the ring main.

Let us preserve a sense of balance as regards the normal provision of plugs every few feet round a room. However many plugs are put in flexible leads to apparatus will still be needed. Two plug points in the room of a dwelling house are quite ample to supply all the average consumer's needs without having a flex longer than 6 ft. Surely the authors do not suggest that 6 ft of flex is more dangerous than 3 ft, or that it is difficult to handle. Actually 6 ft of flex is probably the better of the two.

Mr. S. C. Dinenage (*communicated*): Some speakers stress the disadvantage of the ring-main system or modified ring main for the utility-socket circuit without making sufficient allowance for its undoubted advantages. The main problem involved is one of adequate protection for connected apparatus and flexible conductors, and if, as suggested, the maximum load on the ring can be taken as an occasional 8 kW, a 40-amp (carrying) fuse must be used in the feed to the ring, assuming it is not intended to protect each end of the ring with a fuse. Consequently, a fusing current of some 80 amp is possible, which renders the use of a local fuse essential.

The most convenient form of local fuse would seem to be the fused plug using a small cartridge-type fuse; to prevent the use of non-fused plugs this requires a new socket unit with which existing plugs could not be used. Many people view with disfavour the proposal to introduce another size of socket-outlet, but if either a ring-main or a group-feed system is adopted there appears to be no reasonable alternative to the fused plug.

The proposal in Part 2 that the 5-amp British Standard socket be uprated to 10 amp is a sound one where present-day circuit requirements are met, but in addition to the need for non-interchangeability with existing non-fused plugs it will be found that the terminal arrangements of the 5-amp socket are too small to allow looping-in of relatively large-area conductors.

The design of the proposed service panel is attractive, but the designers appear to have overlooked the opportunity they have to introduce plug-in watt-hour meters which would eliminate loose "tails" and exposed wiring, apart from other and obvious advantages. Also the fuse compartment should be constructed to be child-proof, for the usual mounting position will bring this part to a convenient height for small fingers.

Conductors have not received much attention. I feel that the war-time development of the aluminium industry may find an outlet after the war in the provision of a busbar system using, say, aluminium tube sheathed with bakelized paper which could be built into the fabric of a new house, not necessarily in the form of a specially-moulded skirting as envisaged in the paper, which would be relatively expensive, but more as an omnibus conducting system feeding all parts of the house.

Finally, as one who occasionally keeps uncertain hours I would put in a plea for the silent switch. The authors do mention it, but in view of proposals to use building materials which may be considerably worse, acoustically, than the usual brick and plaster construction, silence of operation will become even more important in the future.

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSIONS

Messrs. Forbes Jackson and W. J. H. Wood (*in reply*): The discussions at the Local Centres generally followed the lines of that in London, but they showed that on some points different views are held in different parts of the country. The proposed universal domestic plug is an example.

In London and the South, there is general agreement that 10 amp would be sufficient for all normal, portable domestic apparatus. At the Local Centres, only 4 speakers agreed with this, while 11 wanted 15 amp, and most of these were prepared to accept the existing 15-amp plug as the universal plug for all purposes. There is probably some confusion as to what we mean by portable apparatus. The engineer of one of the largest municipal undertakings in London stated that 97% of the portable apparatus sold or hired by his department was 2 kW or less. The catalogue of one of the principal makers of electric fires shows nothing over 2½ kW, even in the most expensive models. In the small houses, with which our paper was chiefly concerned, there will be no rooms larger than, say, 160 ft^2. No one can need a 3-kW radiator in such a room, and no one would use one unless he had been ill-advised by the supply authority, who, as Mr. Raven says, "want to sell electricity." It should be borne in mind that this 160-ft^2 room will have a solid-fuel fireplace as well as plug points. Cookers, water heaters and wash boilers are not portable appliances and were not meant to be catered for by the ring main and the universal plug.

At the same time, we agree that we should like the 10-amp plug to have a reasonable overload capacity, and this is one of the reasons why we disagree with those who want to up-rate the 5-amp plug to 10 amp. A 15-amp plug is hardly suitable for universal use for wireless, table lamps and other small consumers. It was not designed for this purpose, and it would be possible with materials and technique now available to produce a much smaller and neater plug with equal current-carrying capacity and incorporating an h.r.c. fuse.

Many estimates, carefully prepared, show a considerable saving in the ring-main technique, but all this saving may be lost if we use an unnecessarily expensive socket and plug. The fuse can be incorporated in the plug as safely as, and more cheaply than, in the socket, and there are other advantages as well. Because of the cessation of building we are now in a position to revise our standards, if there are sound technical advantages, with a minimum inconvenience to the user. Manufacturers should be invited to put forward their best proposals for a new fused plug to carry 10 amp, or, say, 3 kW at 230 V, to have shuttered sockets, to take a 70/·0076 flexible and to connect to a 7/·029 ring main, to fit into a small circular B.S. box, to be semi-sunk, and as neat

and unobtrusive as possible. Ease of insertion and withdrawal would be considered important.

Many speakers referred to the controversy of lug grip versus screwed conduit. In the reply to the London discussion this was dealt with in some detail. Sheffield speakers spoke highly of the lasting qualities of capping and casing. We agree entirely and can point in our own experience to a disastrous fire wrongly attributed to capping and casing, which was ultimately shown to be due to a piece of unearthed conduit resting on a compo gas pipe. As a surface job for wiring existing buildings, it was a very good system, but t.r.s. is a very good alternative. Our advocacy of conduit was, however, for new construction, and for this purpose we still consider buried conduit to be the best solution. We see no objection to insulated systems and should welcome non-conducting conduit if it cost no more than steel. The bogey of wireless interference from unscreened wiring need not, we think, be taken too seriously. There is more trouble caused by intermittent continuity on faulty conduit runs, than by entirely unscreened wiring.

Some speakers criticized Part I as not being sufficiently revolutionary. It was not meant to be. It contained practical proposals for getting on with the job as soon as building began again. It chose the best materials available for this particular purpose of wiring small houses and was based on the experience gained in wiring and maintaining about 100 000 dwellings.

Messrs. G. Smith and **E. Jacobi** (*in reply*): The discussions at the various provincial Centres took place between November, 1943, and March, 1944, that is a year after the paper was first read in London. During that time many of the suggestions in the paper have proved to be of interest, and some are being incorporated in experimental installations now being put in or tested. While carrying out these experimental installations, certain of the ideas expressed in the paper have been developed, and the following reply to the points raised at the discussions takes these developments into account.

Several of the points raised in the provincial discussions were originally raised in London. No further reply to these points has been made here, and reference should be made to our reply to the London discussion.* Also in these provincial discussions, some of the points raised were duplicated, and it is therefore proposed to reply to the discussions as a whole rather than to individual speakers.

Combined service equipment.—Many designs of combined service equipment are taking shape, and the idea has received wide acceptance. The objection has been raised that consumers cannot go back to a flat-rate tariff, but it should be remembered that (*a*) the tariff proposals are not inherent in the service unit as such, which could be designed for separate metering of lighting and power supplies without difficulty, and (*b*) it is most unlikely that, when the value to the consumer of the two-part tariff is fully realized, more than an infinitesimal proportion of consumers will wish to go back to the flat-rate tariff.

The ring main and the skirting.—The installation of the ring main in a skirting specially designed to receive it has also received considerable attention in the past year. It is not always appreciated that two distinct facilities are involved here, namely (*a*) the use of the ring main to allow a number of socket-outlets to be connected to the one ring, and (*b*) the use of the skirting to allow sockets to be added later. It is possible to use the two facilities separately, i.e. to provide a ring main to a given number of positions, the route of the ring main being across the floor or ceiling and independent of the skirting; or, alternatively, to provide socket circuits in the skirting without necessarily being connected to a ring main. The suggestion of a complete ring main in the skirting gives, of course, the maximum facilities both for present use and later additions.

It should be borne in mind that the ring main may very well be provided in the vertical plane and that, where necessary, branches may be run to certain sockets; by doing this the gaps in the external wall, which occur on the ground floor only, can be completely avoided, and fireplaces and interior doors on either floor circumvented by a little thought in routing the ring.

Sockets, plugs and fuses.—Much discussion arose, and further discussion has appeared in the technical Press, in regard to the future development of sockets, plugs and fuses, but there is general agreement that: (*a*) one size of socket should be used for all purposes; (*b*) if the circuit controlling the sockets is controlled by a 10-amp fuse, no local fuses are necessary; (*c*) if the circuit is controlled by a fuse larger than 10-amp, local fuses are necessary; and (*d*) if local fuses are required, it is preferable to place them in the plug head rather than in the socket. If, then, fused plugs are to be used, it is desirable to have a new standard socket to prevent the use of unfused plugs in the same sockets, and ultimately to do away with the present 2-amp and 15-amp sizes for domestic installations.

H.R.C. fuses.—Many different opinions continue to be held on the subject of h.r.c. fuses for domestic installations, but the only development generally agreed is that either all or none of the fuses in a domestic installation should be of the h.r.c. type.

Circuit-breakers and earth-leakage trips.—The general answer to all comments with regard to the use of circuit-breakers, earth-leakage trips, and other automatic devices, is that there is no objection to their adoption providing that they will operate satisfactorily over a number of years without *any* maintenance, and that they will be economic in first cost.

Apparatus.—Some criticism of the paper has arisen from the fact that it does not deal with domestic apparatus. The kitchen unit illustrated in the paper was put forward to support the argument that the services seriously affected the design of the house, although it was felt that the importance of the subject really called for a separate paper dealing specifically with domestic apparatus. During the past year a number of such papers have, in fact, appeared.

The kitchen unit.—The various incidental criticisms that have been made of the kitchen unit as a whole, or of its component parts, are welcomed. Many designs have been developed in the past two years and many more designs will no doubt be produced in the future, each going a little further towards the ideal. It is only by strong and healthy criticisms of the suggestions already put forward that we shall ultimately arrive at the ideal solution.

Finally, the authors wish to express their pleasure in the interest displayed in the discussion of the paper at meetings at eight Centres. Such criticisms as have been voiced have invariably been helpful and have shown that the suggestions in the paper have filled a gap which will assist in the adequate provision of electrical facilities in the huge building programme that lies before us.

* *Journal I.E.E.*, 1943, 90, Part II, p. 475.

AN ANALYSIS OF THE LOAD ON A MODERN ELECTRICITY-SUPPLY SYSTEM*

By P. SCHILLER.†

(*The paper was first received* 14*th October*, 1943, *and in revised form* 7*th January*, 1944. *It was read before* THE INSTITUTION 16*th March*, 1944.)

SUMMARY

The paper contains an analysis of the load on the system of the Northmet Power Co. during a pre-war year. The block of annual load is split up into a basic, or all-the-year round, portion, and a seasonal portion, the latter representing all the consumption due to space-heating, and about half that due to lighting. The basic portion is sub-divided into its principal components, and, as regards the seasonal portion, an attempt is made to separate lighting load and space-heating load, both as to demand and annual consumption. For this purpose "seasonal demand curves" are developed, in which the load at a certain time of day is plotted for a series of days, and compared with the simultaneous conditions of outdoor temperature and illumination. The annual load factors of modern lighting and space-heating loads are found to be normally of equal order of magnitude; in a year with a "cold snap" the load factor of the latter may even be considerably lower than that of the former.

Characteristic collective and component load curves are given; and also graphs dealing particularly with the space-heating load. The paper concludes with recommendations for further research.

(1) INTRODUCTION

One of the fundamental considerations of electricity-supply economics is the study of the characteristics of the load created by the various uses to which electrical energy is put. It has therefore been considered useful to attempt an analysis of the collective load on a modern comprehensive electricity-supply system. By the courtesy of Capt. J. M. Donaldson, all the necessary data and information relative to the system of the Northmet Power Co. were made available. The analysis covers the year ended 30th June, 1939, i.e. the last two consecutive half-years preceding the outbreak of the present war. This period was conspicuous by a cold snap which occurred in the second half of December, immediately following a period of unseasonably mild weather.‡

Every effort has been made to base the analysis on as many facts as possible, with a minimum element of conjecture. The science of load research is, however, still capable of much further development, and investigations of this kind cannot be conducted without resorting to some measure of assumption and estimation.

(2) GENERAL PARTICULARS OF THE SUPPLY SYSTEM

During the period under consideration the area supplied covered 650 square miles, chiefly suburban, with a population of 1·2 million. Of the 36 individual undertakings involved, 31 belonged to the Northmet Co. and the remainder received bulk supplies.

There are three selected stations and two grid-supply points. Main transmission is at 33 kV, and h.v. distribution at 22 kV, 11 kV and 3 kV. The collective load, during the period under consideration, is illustrated by the load model depicted in Fig. 1. The collective m.d. was of the order of 300 MW.

From the statistical data tabulated in Section 3 the character of the consumption can be seen. Owing to its size, the system concerned may be considered representative of average suburban conditions in the Greater London area.

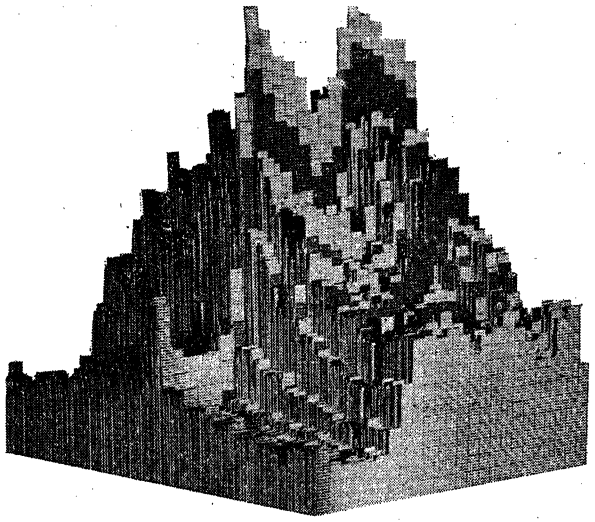


Fig. 1.—Load model.

Constructed by cutting out daily load curves in contour and stacking them with their time bases side by side.

(3) STATISTICAL DATA

The values given in Table 1 have been estimated from the returns for the calendar years 1938 and 1939. By way of comparison, kWh-consumption values for the whole country are also given, derived by increasing the corresponding figures in Table 37 of the Electricity Commissioners' 15th Return (1937–38) by percentages believed to cover the intervening development. It will be seen that although the cooker saturation (Table 2) was rather below the national average (usually assumed to be of the order of 15%), the kWh sold per domestic consumer exceeded the corresponding national average by about one-third. The explanation seems to lie in the comparatively higher level of income, prevailing "all-the-year-round" use of electric cookers, and more extensive application of electric space-heating.

Domestic sales accounted for about 44% of the total, the national average being of the order of 25%.

The average consumption per commercial consumer agreed more closely with the corresponding national average, whereas the kWh sold per industrial power consumer were much below the corresponding national average. This difference is explained by the absence of heavy industries.

(4) POWER AND ENERGY LOSSES

The daily load curves available included the demand of power-station auxiliaries. This made it necessary also to deal with these auxiliaries, instead of confining all considerations to the system load only.

* Based on Report Ref. K/T108 of the British Electrical and Allied Industries Research Association.

† British Electrical and Allied Industries Research Association.

‡ Similar cold snaps occurred in January, 1940, and January–February, 1942.

Table 1

NUMBER OF CONSUMERS AND kWh SOLD

	Domestic			Commercial	Industrial power	Traction	Public lighting	Total
	"All-in"	Others	Total					
Number of consumers	239 600	145 000	384 600	30 000	5 400	—	—	420 000
%	*(62)*	*(38)*	*92*	*7*	*1*	—	—	*100*
kWh × 10^6 sold	280	43*	323	102	216	86	13	740
%	*(87)*	*(13)*	*44*	*14*	*29*	*11·5*	*1·5*	*100*
kWh per consumer	1 170	295*	840	3 400	40 000	—	—	—
Average for country, kWh	—	—	620	3 000	75 000	—	—	—

* This figure contains some consumption for thermal purposes, since cooking and heating supplies at flat rates are included.

Table 2

DOMESTIC COOKING AND WATER-HEATING APPLIANCES

Type	Number installed	% of number of domestic consumers
Cookers	43 000	*11*
Water-heaters	15 000	*4*
Washboilers	11 500	*3*

As set out below, there existed a difference between energy sent out and sold, of 109 × 10^6 kWh, or 15% of that sold.†

	kWh × 10^6
Energy generated and purchased	889
Energy used on power stations	40
Energy sent out	849
Energy sold	740
Energy lost and unaccounted for	109

The bulk of this difference can be attributed to actual losses. But with "continuous meter reading" (applied to domestic and commercial consumers) and steadily growing sales, there is also an apparent loss due to "unbilled units," in the present case approximately 1% to 1½% of the total energy returned as sold.

For the purpose of the present investigation it is necessary to relate conditions associated with energy sold to conditions associated with the available load curves. This involves allocation of the total losses among the classes of consumers and load considered.

The system comprises about 1¼ × 10^6 kVA of transformer capacity, with an aggregate iron loss of the order of 6 MW, of which, say, 5 MW is effective, corresponding to approximately 44 × 10^6 kWh per year. The total number of meters can be estimated at 450 000. Taking an average shunt loss of 1½ W, the corresponding aggregate constant loss is nearly 700 kW. The average total constant losses may thus be assumed to be of the order of 6 MW, corresponding to roughly 50 × 10^6 kWh per year, or close to 7% of the total energy sold.

In view of the relatively higher losses of distribution transformers, and the fact that the domestic and commercial loads are supplied at low voltage throughout, it seems justifiable to allocate to these loads constant transformer losses to the amount of at least 8% of the respective energy sales.

As regards meter-shunt losses, 1½ W corresponds to approximately 13 kWh a year, and taking an average of 1·1 meter per domestic consumer the loss per consumer is over 14 kWh a year, or 1·7% of the average consumption of 840 kWh.

Altogether the percentage of constant losses chargeable to domestic sales may be taken as being of the order of 10%, and that relating to sales to commercial consumers slightly lower. As regards industrial power consumers, if it is considered that a part of the total sales is effected at high voltage, and that meter losses are relatively insignificant, the appropriate allocation in respect of constant system losses appears to be 3% to 4%.

Turning to the copper losses, in view of h.v. sales and generally shorter distances involved the percentage allocation to power consumers must again be relatively smaller, although the lower power factor may have a somewhat counteracting effect.

The remaining losses, due to meter errors, unbilled units, etc., concern principally the class of domestic consumers.

Table 3 shows the result of these considerations.

Table 3

ALLOCATION OF TOTAL ENERGY LOSSES

	Domestic	Commercial	Industrial power	Traction	Public lighting	Total
Energy sold, kWh × 10^6	323	102	216	86	13	740
Loss allocation, %	18	16	10	12½	15	15
Loss allocation, kWh × 10^6	58	16	22	11	2	109
Total sent out, kWh × 10^6	381	118	238	97	15	849

For the purpose of graphic representation, however, it seems preferable to treat the total constant losses as a whole, without allocation among classes of consumers, so that only 59 × 10^6 kWh (109—50) remain to be allocated. This is detailed in Table 4.

(5) SUB-DIVISION OF THE LOAD

One of the principal objects of this investigation is to derive typical component load curves, and to associate these with the corresponding annual amounts of energy. The ideal would be sub-division according to classes of consumers. So long as a class of consumers can be associated with one well-defined kind

† It should be noted that these are losses between selected stations and consumers' terminals.

Table 4

ALLOCATION OF LOSSES OTHER THAN CONSTANT

	Domestic	Commercial	Industrial power	Traction	Public lighting	Total
Energy sold, kWh × 10^6	323	102	216	86	13	740
Loss allocation, %	9	8	7	7	8	8
Loss allocation, kWh × 10^6	29	8	15	6	1	59
Sales + allocated losses, kWh × 10^6 ..	352	110	231	92	14	799

of load, e.g. industrial power or traction, this is feasible. In the case of composite loads, however, difficulties arise. The course taken here is to segregate, in the first place, according to classes of load.

Examination of the load model, Fig. 1, suggests that the total body of annual load may be divided readily into a "basic" or all-the-year-round portion, and a superposed seasonal portion. The latter is chiefly affected by two variables—outdoor illumination and temperature. The former portion can be sub-divided into the following components:* (*a*) Power-station auxiliaries, (*b*) constant losses, (*c*) traction, (*d*) domestic cooking and water-heating, (*e*) industrial power, (*f*) "basic" (all-the-year-round) lighting, (*g*) miscellaneous, largely domestic, uses (excluding lighting and space-heating).

Of the essentially seasonal component loads, lighting and space-heating, the former contains an appreciable all-the-year-round portion, owing primarily to the fact that there is always a daily period of darkness, the minimum interval between sunset and sunrise being, in this area, about 7½ hours. With normal Summer Time, less than 2 hours of this minimum overlap the daily period of human activity, and if Double Summer Time were to be adopted as a permanent feature "basic" lighting would be confined essentially to all-night lighting. The seasonal minimum of the space-heating load, however, is definitely zero.

All seasonal variations are superposed on a steady rise due to a progressively increasing number of connections and intensified individual use. During periods of business depression the trend line may, of course, decline. In the case under consideration the annual overall increase was of the order of 10%. This value will be taken as applying to both normal demand and consumption, and no differentiation will be made in respect of the individual component loads.

(6) METHOD OF ANALYSIS

(6.1) General Plan

For dealing with the basic or "all-the-year-round" loads the two-dimensional daily load curves suffice. It is, however, advisable to eliminate accidental variations and to derive typical curves. If taken to the highest possible degree of accuracy, seven basic daily curves would be required, one for each day of the week. The object of the present investigation is, however, adequately fulfilled by establishing only three basic days, Sunday, Saturday and average working-day.

For studying seasonal variations recourse must be had to the third dimension of the annual load model. If, as in the present case, the daily load curves are already composed of hourly demand values, the whole body may be taken as representing 8 760 such values in 24 rows of 365 each. The sum total of these values is equivalent to the total energy supply involved. Each row depicts the annual variation of the demand associated with one particular hour of the day. In practice it is necessary to sub-divide according to days of week, and in the light of the preceding considerations the annual load model may be conceived to be split up into three, one containing all the Sundays, another containing all the Saturdays, and a third containing all the other days. In this way, instead of 24 series of 365 values we obtain 2 × 24 series of 52 each, and 24 series of 261 each. Each of these series can be plotted in the form of a load curve depicting, not progressive variation in demand, but variation of the demand at a particular time of the day over a series of days. By relating each of these seasonal demand curves to the concurrent conditions of outdoor temperature and illumination, some analysis as to temperature-related and light-related components can be made. This is described in Section 6.2.

The same curves also serve for deriving the above-mentioned daily load curves for the three basic days. Fig. 2, for example, shows the annual variation of the system demand at 8 h–9 h* of all the working-days of the year under consideration. The corresponding temperature is plotted to an inverted scale at the top. By drawing a straight line between the demand points corresponding to the warm days of the first half of July 1938, and those of the end of June 1939, the "basic demand" attributable to the hour 8 h–9 h of working-days is obtained. The gradient of 1 : 10 tallies well with the assumed annual trend of + 10%. As may be seen, the line keeps above the depression surrounding August Bank Holiday, and remains above the minima caused by abnormal mornings. This line of basic demand may also serve as a datum line in respect of seasonal demand variations.

Having obtained the 3 × 24 basic hourly-demand values, the daily load curves can be drawn for the basic Sunday, working-day, and Saturday. The values plotted in Fig. 3 are the mean values for the year, corresponding to the intersection of the respective basic-demand lines with the mid-ordinate. The dotted lines over the period 20 h–24 h show the shape the curves would probably assume if there had been no lighting demand except that existing all round the clock. This estimate is based on load curves obtained under present conditions of Double Summer Time (see Appendix 10.1).

(6.2) Seasonal Supply

It appears preferable first to describe the detailed analysis of the seasonal supply. There are two chief lines of approach: (1) To compare the load curves of characteristic days, and (2) to analyse the above-mentioned seasonal demand curves.

For easy reference, each day of the year is given a symbol, composed of a letter with numeral subscript: Sunday = S, Monday = m, Tuesday = t, Wednesday = w, Thursday = d, Friday = f, and Saturday = s. The first, incomplete, week of the year under consideration is designated by the subscript 0, and the following are numbered 1 to 52. Thus t_{25} describes the Tuesday of the 25th week.

Meteorological references are based on observations at Kew, as recorded in the Daily Weather Report of the Meteorological

* All these components are, of course, subject to slight seasonal variations. No account is taken of specific summer loads, such as those due to nursery and drainage pumping, refrigerators, fans, etc., since they are comparatively insignificant.

* Time of day is expressed on the basis of the 24-hour system.

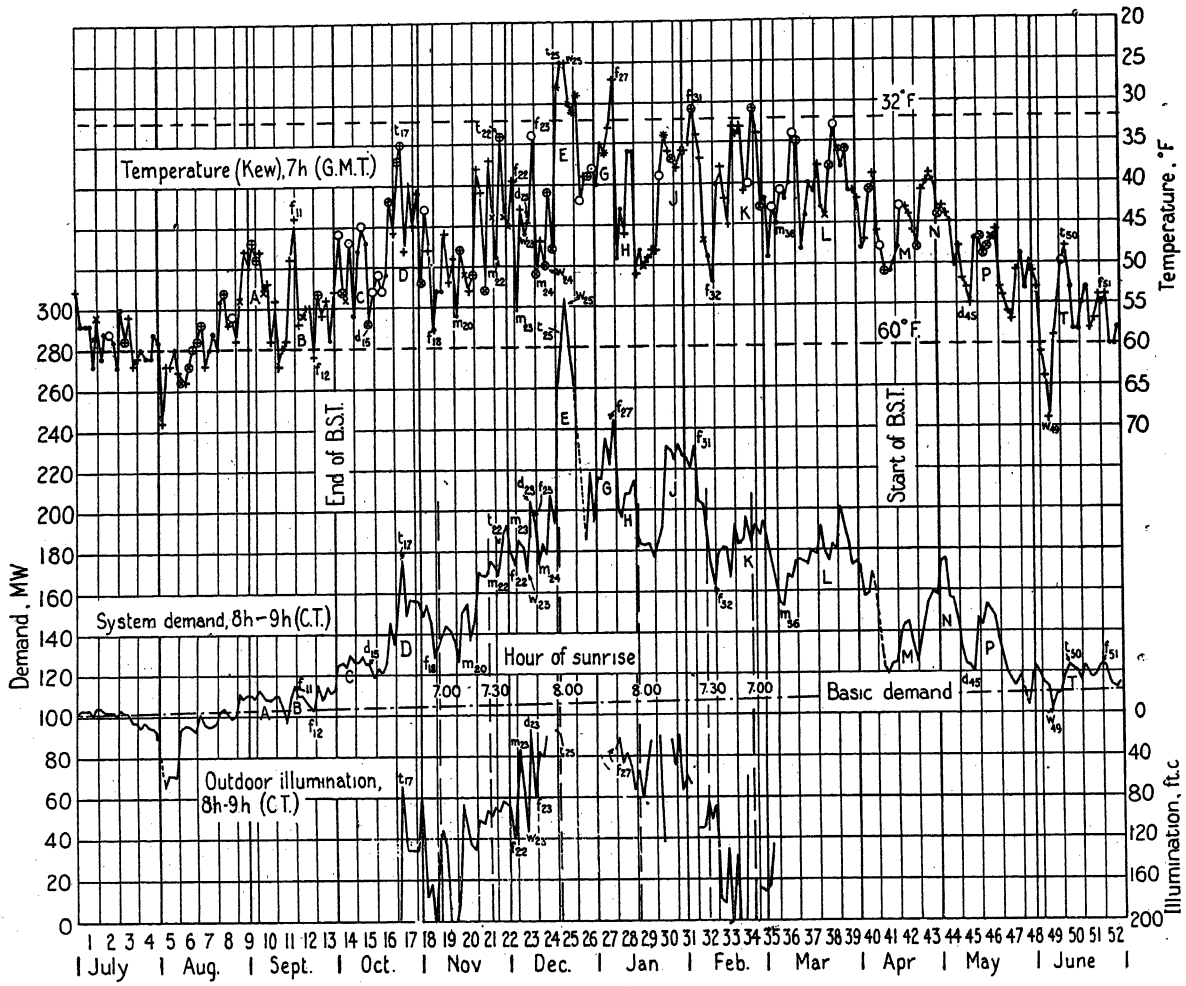


Fig. 2.—Seasonal variation of the demand at 8 h–9 h of working-days.

Office. In plotting temperatures the following symbols for indicating the simultaneous weather conditions have been used.

- ○ Sky not more than half-covered with cloud.
- ● Generally cloudy or overcast.
- \+ Dust haze; the turbid atmosphere of dry weather.
- ⊕ Mist or fog.
- × Rainy (drizzle, showers or rain).
- ⊗ Continuous rain.
- ✱ Snow.

The same symbols have also been applied in connection with daily load curves. In addition, force and direction of wind are there given by means of arrows and feathers as used in the weather charts of the Meteorological Office, namely arrows flying with the wind (direction of north, east, etc., as on maps), a short feather indicating one step on the Beaufort Scale, and each full-length feather two steps (e.g. generally cloudy, south-westerly wind, force: 3).

Outdoor illumination is, of course, chiefly determined by the position of the sun. Fig. 4 shows clock times of sunrise and sunset for the year concerned. The exact times when artificial indoor lighting may have become necessary or dispensable depend on meteorological influences. Taking, for example, the hour 7 h–8 h, all one can say is that up to the end of October

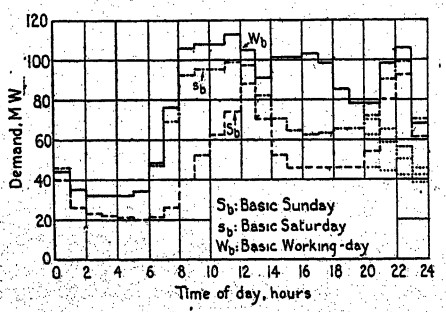


Fig. 3.—Load curves of basic Sunday, working-day, and Saturday.

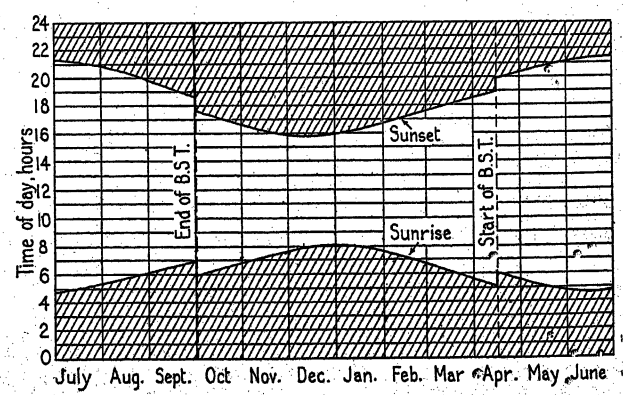


Fig. 4.—Sunrise and sunset (clock times), July 1st, 1938–June 30th, 1939.

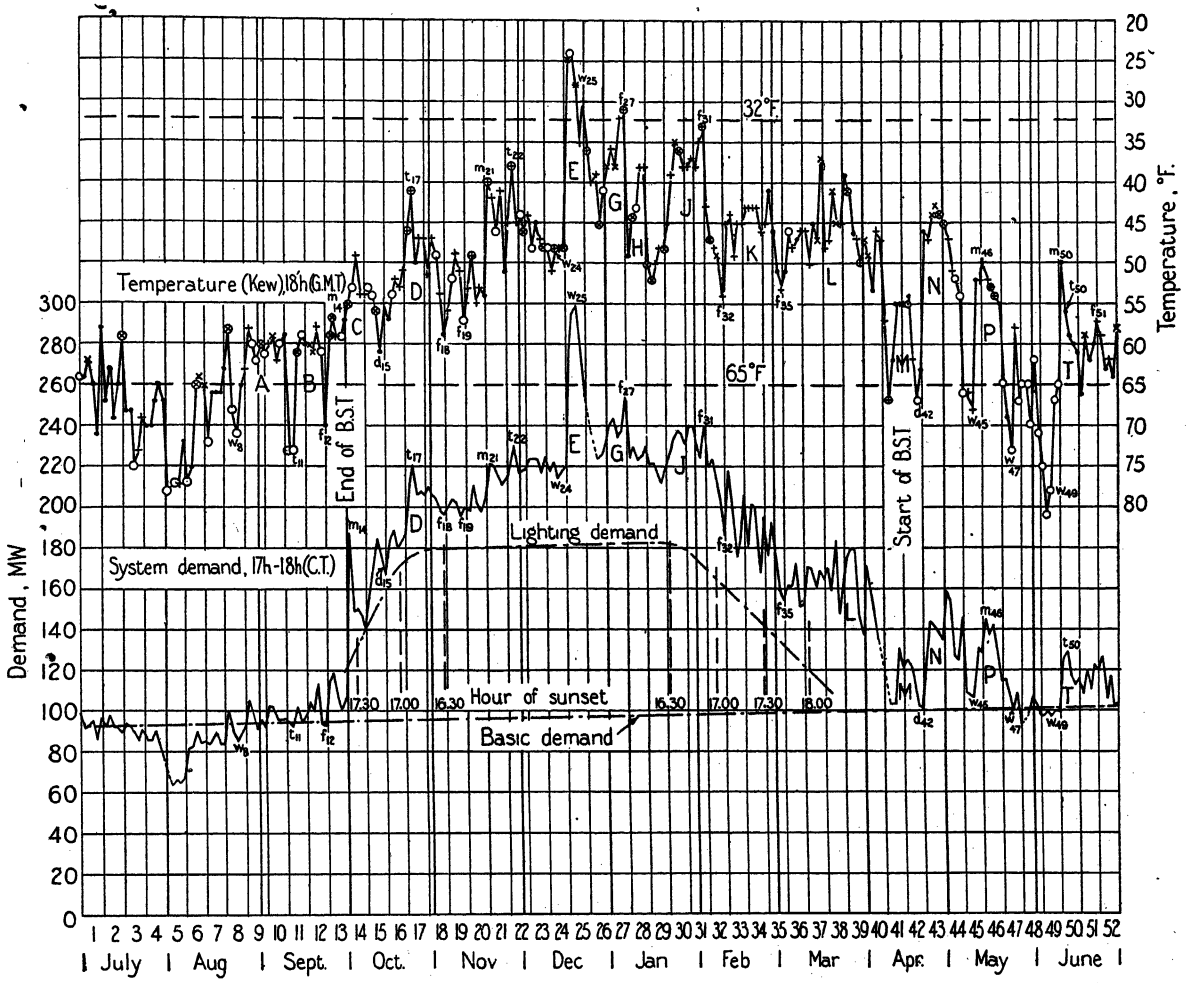


Fig. 5.—Seasonal variation of the demand at 17 h–18 h of working-days.

it normally will entail no appreciable seasonal lighting demand, then there will be a period of transition in which atmospheric conditions will have great effect, until at the end of the calendar year this hour will be almost completely dark, and so forth. The only exact basis, especially for the period of transition from full daylight to full darkness, is actually measured outdoor illumination. The corresponding values in foot-candles describe the variable "outdoor illumination" in the same way as degrees F describe the variable "outdoor temperature."

As it happened, during the period under consideration the National Physical Laboratory had carried out daylight recordings to find average values for the use of architects, etc.* By the courtesy of Dr. J. W. T. Walsh of the N.P.L. the detailed records of the tests have been made available, but since they refer to varying quadrants of the sky they are not strictly comparable within themselves.

The detailed procedure will now be described, first with reference to Figs. 2 and 5–7. It will be seen at a glance that the patterns formed by the inverted temperature curves are well reproduced in the corresponding demand curves,† proving that outdoor temperature is the chief determinant of space-heating demand. The main "ripples" superimposed on the inverted annual wave are designated A to T. As reproduced in the demand curves, these ripples are clearly due to space-heating demand only, whereas the long-wave variation is a combination of space-heating and lighting demand. Chilly September mornings already produce some space-heating demand (A and B), and even in June there are traces of such demand (T).

From Fig. 4 can be seen that the hour 8 h–9 h is what may be called a "fringe hour," i.e. it never becomes completely dark. To enable further study to be made, some vertical lines have been added in Fig. 2 indicating the days when the sun rises at 7 h, 7.30 h and 8 h, respectively, and at the bottom of the diagram the mean illumination (with reference to a quadrant of the sky) for the hour 8 h–9 h of the days of the corresponding period has been plotted (as far as available from the above-mentioned N.P.L. tests). Comparing the adjacent points w_{23} and d_{23} as indicated on the three curves, it may be seen that the difference in demand (35 MW) can be attributed to a striking difference in outdoor illumination, since the corresponding meteorological conditions were practically identical. It may further be seen that the illumination value associated with d_{23} is the lowest of all recorded, and that on a really cold morning the illumination may be rather higher (cf. f_{23}, t_{25}, f_{27}). On the light morning of w_{23}, too, there was probably some lighting in use, the corresponding demand being somewhere between 10 and 20 MW. Thus it may be concluded that the m.d. for lighting purposes during the hour 8 h–9 h was of the order of 50 MW, and that on cold mornings the demand was lower, say 35 MW.

In the case of "fringe hours," such as that just considered, it is impossible to apportion the integrated seasonal demand (total area under the seasonal demand curve less integrated basic de-

* Department of Scientific and Industrial Research: "Seasonal Variation of Daylight Illumination" (H.M. Stationery Office, 1935).

† The dotted portions of these curves cover gaps caused by the omission of holidays.

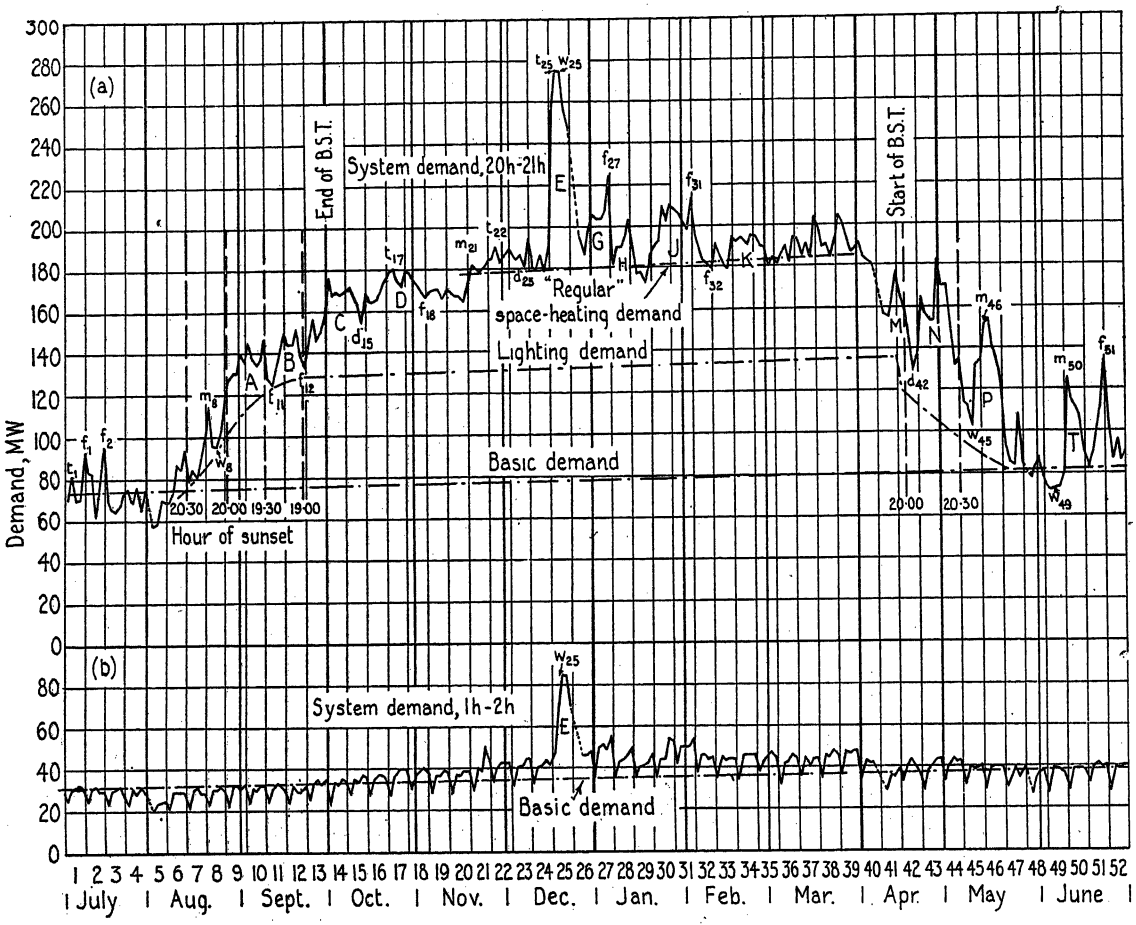


Fig. 6.—Seasonal variation of the demand at (*a*) 20 h–21 h, and (*b*) 1 h–2 h on working-days.

mand) correctly between lighting and space-heating demand. Here recourse must be had to estimation, but as regards the hour 8 h–9 h it is obvious that the bulk of the consumption due to seasonal demands is attributable to space-heating.

Fig. 5 represents the conditions at the hour of overlap between decreasing industrial and increasing domestic activity. Characteristic features are the relatively diminished reproduction of temperature ripples during the period when coal fires are used intensively, and the easily-discernible block of sustained lighting-demand due to the hour in question being completely dark for a number of months (cf. Fig. 4). The heavy fluctuations of demand due to varying conditions of the sky during the period of transition between the hours of sunset of 17 h and 17.30 h, especially in February, should be particularly noted.

The approximate seasonal lighting-demand attributable to the hour under consideration can be ascertained with comparative accuracy. In doing so the assumption is made that during the annual period in which an hour is completely dark there will be only minor fluctuations in the corresponding lighting-demand,* though there will be some progressive relative increase due to "trend." The best basis for examination is the period of transition from light to dark in autumn, when the masking effect of the space-heating demand is not so pronounced as in spring.

When the sun sets at 16.30 h, the hour 17 h–18 h may be assumed to be completely dark and lighting demand at its full value relative to the hour in question. From a comparison of characteristic daily load curves, described later, the simultaneous space-heating demand on the mild November day f_{18} is estimated to be of the order of 20 MW, and by considering an increase of 10% per annum due to trend the inclined line marked "Lighting demand" is evolved. It intersects the mid-ordinate at 182 MW, and if from this value is deducted the corresponding basic demand of 98 MW, the seasonal lighting-demand attributable to the hour 17 h–18 h results as 84 MW. The slope given to the lighting-demand curve during the periods of transition rests, of course, on hypothesis, although at the autumn period some guide is provided by warm days (e.g. d_{15}).

The demand at the hour 20 h–21 h, being to a great extent of domestic origin, is depicted in Fig. 6(*a*). The temperatures of the particularly warm days w_8, t_{11} and f_{12} (compare temperature curve in Fig. 5) in conjunction with the times of sunset thus enable the lighting-demand curve to be developed with particularly good accuracy. Here, the whole of the excess over the latter curve, as well as over the extensions formed on both sides by the line of basic demand, can be attributed to space-heating. It is noteworthy that even June and July evenings may bring about a space-heating demand of the order of 30 to 50 MW (see t_1, f_1, f_2, m_{50} and f_{51}).

The line designated "Regular space-heating demand" indicates the level of space-heating demand sustained during the cold season, independent of temperature variations. Nearly 50 MW may thus be attributed to electric space-heaters used consistently every evening in winter.

Fig. 6(*b*) shows how little seasonal variation accompanies the hour 1 h–2 h. The outstanding feature is E, i.e. an all-night demand of about 40 MW due to domestic space-heating for the

* In the past much used to be made of the increase in shop-lighting demand before Christmas. How small the relative present proportions of shop-lighting demand are can be seen from the fact that although in the greater part of the area of supply Thursday is early-closing day, the drop in demand, if discernible at all, is only of the order of a few MW.

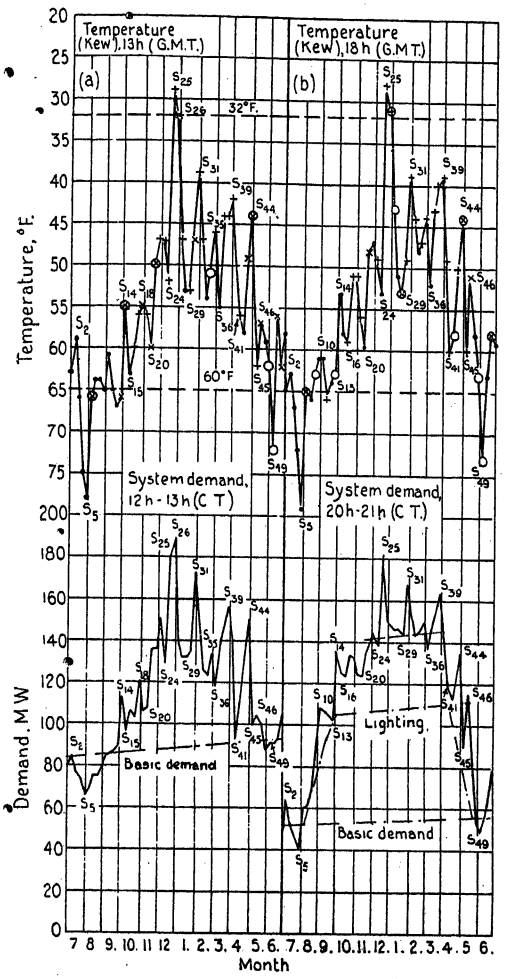


Fig. 7.—Seasonal variation of the demand at (*a*) 12 h–13 h, and (*b*) 20 h–21 h on Sundays.

prevention of pipe-freezing. The serrated shape of the curve may be explained by the absence in the night from Sunday to Monday of a 3-shift power load of approximately 10 MW.

Finally, two specimens of Sunday curves are reproduced in (*a*) and (*b*) of Fig. 7. Since there are intervals of one week between adjacent points, waves and ripples are now much steeper. In the curve for the hour 20 h–21 h the "regular space-heating demand" is only of the order of 35 MW. The curve relative to the hour 12 h–13 h is further developed in Appendix 10.3.

The basic temperature, i.e. the level below which the various seasonal demand curves become temperature-sensitive, seems to be between 60° F and 65° F. The lower value applies to the morning.

From the curves shown the following characteristic working-days have been picked out:—

(i) A cold-snap day (w_{25}).
(ii) An ordinary cold winter day (f_{27}).
(iii) A relatively mild December day (w_{24}).
(iv) An unseasonably warm November day (f_{18}).
(v) A mild October evening (d_{15}).
(vi) A warm September evening (f_{12}).

In Fig. 8 the corresponding daily load curves are compared with one another and with the curve of the basic working-day (Fig. 3). The meteorological conditions as well as the hours of sunrise and sunset are also indicated.

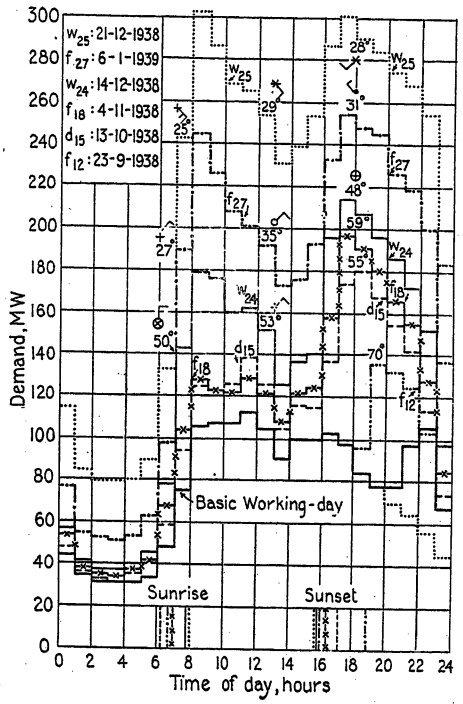


Fig. 8.—Comparative working-day load curves.

The lighting peak of the basic working-day can be associated with a sunset at about 21 h B.S.T. On the day f_{12} the sun set at 19 h, so that from 20 h daylight may be assumed to have ceased and lighting demand to have been at its full value; and although, in the course of the evening, the outdoor temperature will have fallen somewhat below the value of 70° F recorded at 19 h, only a very small amount of "fireside" heating may be expected. Thus the demand values for the period from 20 h to 24 h of the day f_{12} may be taken to consist of basic demand plus lighting demand, with a trace of space-heating demand.

On the mild October evening d_{15}, however, space-heating demand was obviously higher, but with sunset at 17.14 h the hours 18 h–19 h and 19 h–20 h were also completely dark. The exceptionally warm November day f_{18} showed a small increase, mainly due to space-heating, over the basic day all through the daylight hours, and in the evening still more space-heating than d_{15}. With the sun setting at 16.30 h complete darkness has now virtually reached the hour 17 h–18 h, and allowing for a space-heating demand of 10 to 15 MW during the daylight hours, rising to 30 to 40 MW in the evening, the shape of the load curve of this extraordinary day is characterized by the demand due to lighting.

By utilizing seasonal demand curves and daily load curves in conjunction, it is thus possible to develop approximate load curves for the maximum normal lighting load for Sunday, working-day and Saturday, as illustrated by Fig. 9.

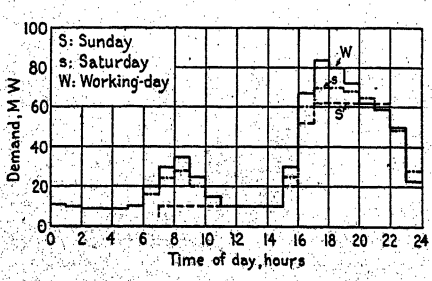


Fig. 9.—Lighting load: characteristic daily load curves.

If it is now assumed that the difference between the total load curve for a cold winter day and the combined curve of basic demand and lighting-demand represents the demand due to space-heating, characteristic daily load curves of the space-heating load can be derived.

Fig. 10 shows some of the results. The curves for the three "ordinary" cold days are not strictly comparable, since the meteorological conditions were not equivalent.

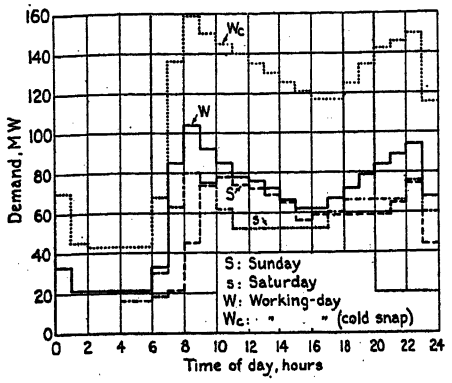


Fig. 10.—Space-heating load: characteristic daily load curves.

As a general inference it can be stated that on cold days the space-heating load produced by the system in question showed two distinct peaks, one in the morning (8 h–9 h on working-days) and one in the late evening (22 h–23 h, obviously due to bedroom heaters), and that the two peaks were virtually of the same order of magnitude. On working-days there was an almost symmetrical valley between the morning and the evening peak.

Reverting to the task of apportioning the annual seasonal supply as between lighting and space-heating, after the 3 × 24 seasonal demand curves have been analysed in conjunction with the selected characteristic daily load curves, and the probable lighting-demand curves inserted, three statements, illustrated for working-days by Table 5, can be prepared.

In this hour-by-hour analysis the bulk of the seasonal lighting supply, associated with the hours that are dark for a number of months, can be assessed fairly accurately. The rest cannot be estimated without a certain amount of guesswork. Table 6 gives the overall figures.

Table 5

APPORTIONING OF TOTAL SUPPLY

Working-days

Hour	Total	Basic	Seasonal	Lighting	Space-heating
h	kWh × 10^6	kWh × 10^6	kWh × 10^6	kWh × 10^6	kWh × 10^6
0–1	13·4	10·8	2·6	—	2·6
1–2	10·0	8·9	1·1	—	1·1
2–3	9·3	8·2	1·1	—	1·1
3–4	9·3	8·2	1·1	—	1·1
4–5	9·5	8·2	1·3	0·1	1·2
5–6	11·0	8·8	2·2	0·9	1·3
6–7	16·5	12·3	4·2	1·5	2·7
7–8	29·0	19·6	9·4	1·8	7·6
8–9	38·0	27·4	10·6	1·2	9·4
9–10	36·5	28·0	8·5	0·5	8·0
10–11	35·5	28·0	7·5	0·3	7·2
11–12	36·0	29·3	6·7	0·2	6·5
12–13	34·5	27·2	7·3	0·2	7·1
13–14	30·0	23·4	6·6	0·2	6·4
14–15	32·5	26·2	6·3	0·3	6·0
15–16	33·0	26·2	6·8	1·0	5·8
16–17	36·5	26·5	10·0	3·7	6·3
17–18	40·0	25·3	14·7	8·4	6·3
18–19	40·5	22·0	18·5	10·2	8·3
19–20	40·0	20·0	20·0	11·0	9·0
20–21	39·0	20·0	19·0	9·6	9·4
21–22	40·0	25·3	14·7	4·9	9·8
22–23	35·5	27·5	8·0	—	8·0
23–24	23·5	17·7	5·8	—	5·8
Total	679·0	485·0	194·0	56·0	138·0

Table 6

BASIC AND SEASONAL SUPPLIES

Days	Basic	Seasonal		Total
		Lighting	Space-heating	
	kWh × 10^6	kWh × 10^6	kWh × 10^6	kWh × 10^6
Working-days ..	485	56	138	679
Saturdays ..	82	10	27	119
Sundays	59	9	23	91
Total	626	75	188	889

Actually, the seasonal supply contains more than the two components hitherto considered. It may be sufficient to take into account only the seasonal component of the supply to power-station auxiliaries, and to deduct the corresponding 10 × 10^6 kWh (see Section 6.3.1) in equal parts from the values computed for the lighting and space-heating components. This leaves 70 × 10^6 kWh for the former and 183 × 10^6 kWh for the latter.

(6.3) Basic Supply

As already mentioned, the analysis of the basic portion of the total annual supply is two-dimensional, i.e. it can be confined to dealing with daily load curves. For the highest degree of accuracy attainable the basic daily load curves of working-days, Saturdays and Sundays would have to be analysed in detail. However, all practical purposes can be served by confining this to the average working-day (Figs. 11 and 12), and considering Saturdays and Sundays only when calculating daily consumption.

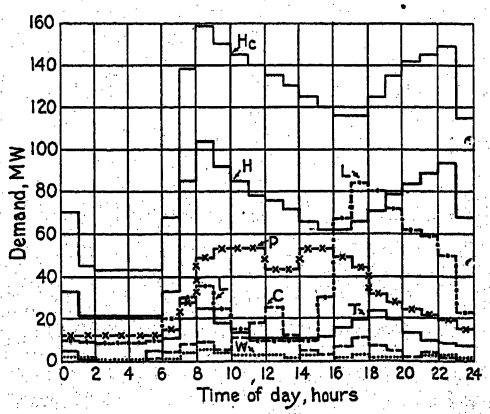


Fig. 11.—Principal component loads.

C: Domestic cooking.
H: Space-heating, ordinary cold day.
H_c: Space-heating, cold-snap day.
L: Lighting.
P: Industrial power.
T: Traction.
W: Domestic water-heating.

(6.3.1) Power-Station Auxiliaries.

Out of 40 × 10^6 kWh, about 30 × 10^6 may be considered to be included in the basic supply, the corresponding demand being of the order of 5 MW.

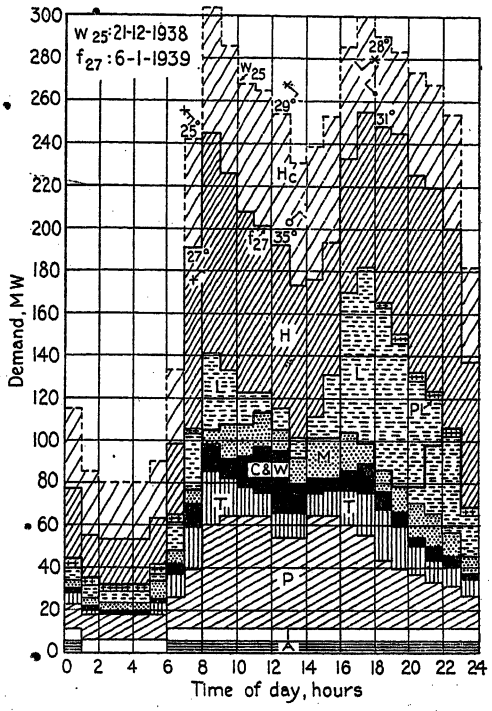


Fig. 12.—Sub-divided working-day load curves.

A: Power-station auxiliaries.
C: Domestic cooking.
H: Space-heating, ordinary cold day.
H_c: Space-heating, cold-snap day.
I: Constant losses.
L: Lighting (PL: Public lighting).
M: Miscellaneous.
P: Industrial power.
T: Traction.
W: Domestic water-heating.

(6.3.2) **Constant System Losses.**

As expounded in Section 4, the constant power losses are taken as having a mean value of 6 MW.

load curve was derived and redrawn on the basis of an m.d. of 25 MW (Fig. 11).

(6.3.4) **Domestic Cooking and Water-Heating.**

Load synthesis provides the means of deriving the estimated daily load curves relative to domestic cooking and water-heating.

From the load curve for the basic Sunday (Fig. 3) it can be seen that the midday peak exceeds the steady afternoon demand by 42 MW. Allowing for water-heater demand—which will be shown to be comparatively small—this value corresponds to an A.D.M.D. (after-diversity maximum demand) of about 0·9 kW per unit of the 43 000 cookers. Another indication is furnished by the difference in the demand associated with Easter Sunday and Monday, or Whit-Sunday and Whit-Monday (provided weather conditions are not too dissimilar). Fig. 14 shows peak differences of 24 and 27 MW respectively. These values give an extra A.D.D. per cooker of nearly 0·6 kW, which can be attributed to oven demand (joint roasted on the first day). With these indications as to the character of the cooking load involved, the A.D.D. values stated in Table 7 have been estimated.* The values relative to water-heaters have been derived from the information contained in E.R.A. Report Ref. K/T105,† which refers to circulator-type heaters, so that adjustments had to be made to take care of the probable actual composition of the 15 000 water heaters connected to the system under consideration.

Annual consumptions, including losses as in Table 4, have been estimated as shown in Table 8.

The total cooker consumption per day would work out at about 165 000 kWh; but since the consumption on a Sunday is, perhaps, twice as high as that on an ordinary weekday, the average working-day consumption is taken as 150 000 kWh. Average total daily consumption of water-heaters results as 62 000 kWh. No adjustment for Sunday consumption appears necessary in this case. Since the use of washboilers is almost exclusively associated with Mondays, the corresponding consumption is not averaged out.

Table 7

COOKER AND WATER-HEATER DEMAND (AVERAGE WORKING-DAY)

		8 h–9 h	12 h–13 h	17 h–18 h	21 h–23 h
Cookers	A.D.D. per unit, kW	*0·2*	*0·6*	*0·25*	*0·1*
	Total demand, MW	9	26	11	4
Water-heaters	A.D.D. per unit, kW	*0·35*	*0·25*	*0·2*	*0·25*
	Total demand, MW	5	4	3	4
Combined total demand .. .. .. MW		14	30	14	8

(6.3.3) **Traction.**

The traction load, being due to a single consumer (L.P.T.B.) and a limited number of substations, can be dealt with comparatively easily. In the total of 92 × 10^6 kWh (Table 4) railways and trolleybuses share approximately equally. The actual load factor of the railway supply was 33·7%, based on the usual half-hour demand-integration period. The influence of the additional trolleybus supply, which is given through various independent substations, may be expected to improve the load factor of the combined supply. Expressed on the one-hour basis used throughout this analysis, the combined annual load factor is estimated at 38%, giving an m.d. of 27 MW. As this applies to a winter day, the m.d. of the basic traction load curve is taken as 25 MW. From typical daily load curves of individual trolleybus and railway substations the estimated shape of a composite

Table 8

Appliances	Annual consumption per appliance	Total annual consumption
	kWh	kWh × 10^6
Cookers	1 500	64·5
Water-heaters	1 500	22·5
Washboilers	350	4·0

With these assumptions as to A.D.D. and daily kWh the load curves for cooking and water-heating load can now be plotted (Fig. 11).

* All demand figures are deemed to include power losses in conductors.

† BOLTON, D. J.: "The Measurement of Water-Heater Diversity by Superimposed Control," *Journal I.E.E.*, 1943, 91, Part I, p. 60.

(6.3.5) **Industrial Power.**

Of the total of 231×10^6 kWh (Table 4) allocated to industrial power supply, some proportion must be considered to have been used for seasonal lighting and space-heating purposes. From a study of the curve of weekly sales this proportion is estimated to be of the order of 10%, so that roughly 210×10^6 kWh are left to be treated as "basic."

The 3-shift load of 10 MW mentioned in connection with Fig. 6(*b*) may be assumed to have existed from Monday, 7 h, till Saturday noon of each normal week. Allowing one week for holidays, etc., this corresponds to 64×10^6 kWh per year. Supposing, further, that there is a constant component of 2 MW due to plant running entirely without interruption, another 17×10^6 kWh can be allocated. The remainder, $210 - (64 + 17) = 129 \times 10^6$ kWh, can be attributed to 1- and 2-shift operation. With 51 weeks and 5½ working-days per week this gives a daily average of 460 000 kWh. If this were due to a single shift of 9 hours' duration, associated with constant demand, the latter would work out at 51 MW, to which would have to be added the (10 + 2) MW of the two other components, making 63 MW altogether.

In practice, however, there is to be considered the effect of staggered working-hours, overtime, 2-shift operation, etc. The demand figures just developed have therefore been taken as an indication of order of magnitude only, and the estimated daily load curve of the industrial power load has been developed by fitting it into the shape of the load curve of the basic working-day, taking into account the more reliably estimated load curves of other components (traction and domestic cooking), and bearing in mind that the area under the resulting curve must correspond to 750 000 kWh (460 000 + 12 000 × 24).

(6.3.6) **Basic Lighting.**

The lighting component contained in the basic supply may be sub-divided into (*a*) a portion associated with the residual evening peak of the basic days (see Section 6.1), (*b*) a portion associated with the hours from midnight to dawn, and (*c*) a portion due to lamps switched on in daylight all the year round. The consumption (including losses as in Table 4) relative to (*a*) works out at 42×10^6 kWh. One element of (*b*) is the demand for public lighting. With 14×10^6 kWh a year and a load factor of 45% an average demand of the order of 3½ MW results. Adding an estimated further 5½ MW attributed to other all-night lighting,* the supply under the head of (*b*) works out at about 18×10^6 kWh. No rational guess can be made regarding (*c*), and a token figure of 5×10^6 kWh is used. Thus the total that can be allocated to "basic" lighting is 65×10^6 kWh.

(6.3.7) **Miscellaneous Basic Components.**

The area between the load curve for the basic working-day and the collective load curve of the components dealt with in Sections 6.3.1 to 6.3.6 can be associated with a number of miscellaneous loads, such as those due to small domestic appliances, commercial motors, all-day lighting, etc.

Estimating the average annual consumption due to miscellaneous domestic applications at 120 kWh per consumer (including losses as in Table 4) the total annual supply under this head works out at 46×10^6 kWh. The corresponding demand may be assumed to be spread over the length of the daily period of activity in the house.

There remains a balance of 42×10^6 kWh, attributable to commercial power consumption and miscellaneous other uses not specifically accounted for. The figure appears quite possible, and confirms the comparative correctness of the sub-division made.

(7) RESULTS

The principal results of the analysis are given in Figs. 11 and 12, and Table 9. In the latter, the m.d.'s of the basic loads may be regarded as averages of a number of actual m.d.'s, according to the process of averaging employed in the corresponding computations. As the resulting load factors do not conform to the conventional definition, which is based on the annual m.d., estimated values of actual m.d. and corresponding load factors have been added in brackets. In the case of the cooking load the daily m.d.'s vary appreciably in the course of the weekly cycle, and this has been considered by assessing the actual m.d. 10% higher than the mean value. Taken by itself the cooking load would have to be judged by its Sunday m.d., which may be higher by something like 50%.

The estimate of the actual m.d. of the industrial power load is included by way of token. It does not consider seasonal extra demand due to lighting and heating at the power rate.

Table 9

RESULTS OF ANALYSIS

Including, excluding, cold snap	Number of kWh		Maximum demand*		Load factor*		Peak hours	
	incl.	excl.	incl.	excl.	incl.	excl.		
	kWh × 10⁶		MW		%		h	
Total supply	889	882	303	256	33½	39½	8–9	17–18
Seasonal supply	263	256	202	158	15	18½	8–9	17–18
Seasonal lighting	70		85		9		17–18	
Space-heating	183	176	160	100	13	20	8–9	22–23
Miscellaneous	10		5		—		—	
Basic supply	626		113		63		11–12	
Station auxiliaries	30		5(10)		—		—	
Constant losses	50		6		—		—	
Traction	92		25(27)		42(38)		8–9	18–19
Domestic cooking and water-heating	91		30(33)		35(31½)		12–13	
Industrial power	210		53(60)		45(40)		8–12	14–17
Basic lighting	65		—		—		—	
Miscellaneous	89		20		39		—	
Total lighting	135		85		18		17–18	

* Based on 1-hour demand-integration period.

* The imposition of the blackout in the second half of 1939 caused the all-night load to drop by about 10 MW.

The space-heating load has been considered on the basis of two alternatives, with and without cold snaps, the difference of 7×10^6 kWh being derived from the excess of the total supply during the cold-snap (25th) week over that during the not extraordinarily cold 28th week.

It would, of course be desirable to sub-divide the lighting and space-heating figures further, especially among the classes of domestic, commercial and industrial consumers.

As to lighting demand, the load curves in Fig. 9 give some indication by showing the probable difference between working-day and Sunday demand. But while it can be assumed that the excess of the former over the latter is due to commercial and industrial consumers, the domestic lighting demand between 17 h–18 h of a working-day is probably lower than the corresponding Sunday demand. In a smaller system some idea of the demand for internal shop lighting could have been derived from the difference between normal working-day and early-closing-day load.

Owing to the dearth of statistical material relative to sub-division of commercial and industrial consumption, a rational attempt at further sub-division must be confined to the domestic supply. Out of the total of 352×10^6 kWh (Table 4) there has been allocated 137×10^6 kWh to cooking and water-heating (91) and miscellaneous basic uses (46), leaving 215×10^6 kWh for lighting and space-heating purposes. Assuming an average consumption for purely lighting purposes of 150 kWh per domestic consumer, the corresponding total works out at 63×10^6 kWh, which leaves 152×10^6 kWh attributable to domestic space-heating. Thus:—

	kWh × 10^6
Total lighting supply	135
Public lighting	14
Private lighting	121
Domestic lighting	63
Other lighting	58
Total space-heating supply	183
Domestic space-heating	152
Other space-heating	31

The inference would be that the supply taken by commercial and industrial consumers for lighting purposes was almost double that for space-heating purposes, whereas in the domestic supply the relation was reversed.

On the basis of the data used the average annual consumption per domestic consumer can be broken up thus:—

	kWh per consumer	%
Lighting	150	*18*
Miscellaneous small appliances	110	*13*
Cooking and water-heating	215	*26*
Space-heating	365	*43*
Total	840	*100*

The Sunday lighting curve in Fig. 9 shows a maximum of 62 MW. With a deduction of 17 MW due to public lighting, other non-domestic lighting and correction for station-auxiliaries demand, the corresponding A.D.D. per domestic consumer works out at approximately 0·120 kW.

According to Fig. 10 the demand due to space-heating at 22 h–23 h of a cold-snap day was of the order of 150 MW. Allowing, say, 20 MW for non-domestic space-heating demand and by way of correction for higher lighting demand, the result is 0·340 kW per domestic consumer.

From Figs. 8(*a*) and 7(*b*) it can be seen that the space-heating demand existing at 20 h–21 h throughout the entire cold season was of the order of 50 MW on working-days and 35 MW on Sundays. Allocating 45 MW of the former and the whole of the latter to domestic space-heating, which at the particular time consists almost exclusively of living-room heating, and assuming an average input of 2·2 kW (including system losses) per electric fire, it can be deduced that roughly 20 000 domestic consumers on working-days and 15 000 on Sundays used electric living-room heating consistently. These figures correspond to 5% and 4% of the total number of domestic consumers.

(8) CONCLUSION

It is of some interest to reflect that if there had been no lighting or space-heating load, the collective load factor would have been around 56%.* Addition of the lighting load lowers this to approximately 44%†, and the further addition of the space-heating load results in the actual value of 33½%(39½%, excluding cold-snap). The respective increments in total number of kWh supplied are 30% and 29%.

The load factor of the space-heating load on the system investigated seems to be lower than that of the lighting load; at the most it is of same order of magnitude.

The daily load curve of the space-heating load produced by a cold day shows two virtually equal peaks, one between 8 h and 9 h and the other between 22 h and 23 h. The latter, caused by bedroom heating, is harmless because of good diversity in respect of the lighting peak. It is the morning peak that may give rise to alarm. Once the total system load is transformed to reach its maximum at that time, any further disproportionate increase in space-heating load is bound to impress its inherent low load factor on that of the collective load.

With the cooker saturation at 11% the midday cooking peak is still well absorbed by the lunch-time dip in the factory load. Disregarding cold-snap conditions, the highest Sunday-midday demand was 170 MW, and the highest working-day demand 256 MW, leaving a margin of 86 MW. Supposing that each additional cooker adds 0·9 kW to the Sunday peak and 0·25 kW to the working-day peak, about 130 000 more cookers could be connected until the Sunday peak reached the working-day peak (providing all the other component loads remained unchanged). The corresponding total cooker saturation would be 45%.

A striking feature is the insignificance of the water-heating load. It was responsible for less than 3% of the total kWh and only 2% of the total m.d. Since both electric cooking and water-heating represent basic supplies, the importance of their cultivation is manifest.

The overall load factor of the domestic load involved cannot be estimated with any great accuracy. The m.d. occurred between 8 h and 9 h. The corresponding demand due to cooking and water-heating was about 15 MW. Miscellaneous small appliances may account for 5 MW. There remains to be allocated a total of 192 MW (cold-snap) or 134 MW (ordinary cold morning) attributable to lighting and space-heating. Allowing 20% for non-domestic sources, which appears generous, 154 MW and 107 MW, respectively, would be chargeable to the domestic load, making totals of 174 MW and 127 MW, respectively. The corresponding energy figures are 352 and, say, 346×10^6 kWh, respectively, and the resulting load factors 23% (with cold-snap) and 31% (without cold-snap). These figures tally with previously-expressed opinions.

		kWh × 10^6
* Actual basic supply		626
"Basic" lighting	65	
Reduction in constant losses	25	90
		536; m.d.: 100 MW
† Actual basic supply		626
"Seasonal" lighting		70
		969; m.d.: 180 MW

Further work on the line of load research thus initiated should comprise:—

(*a*) Similar analyses to be carried out on smaller systems where more details can be obtained as to the actual uses to which the energy sold has been put; also on systems with different characteristics and composition of the consumption; and analyses covering periods of several successive years.

(*b*) Analyses of the consumption of individual commercial and industrial consumers, especially in respect of use made for lighting and space-heating purposes.

(*c*) Analyses of the load due to uniformly equipped blocks of flats and housing estates, particularly with continuous recording of the component loads over extended periods.

(*d*) Synthesis of hypothetical collective loads, on the basis of varying magnitude and nature (e.g. all-electric versus coal-electric space-heating) of components (after the characteristics of the component loads have been more firmly established) so as to find the optimum goal of development.

Hand in hand with the work under (*d*) would have to go a scientific establishment of bases for calculating and comparing costs of supply, particularly in connection with growth of demand, to enable each hypothetical variant of load development to be coupled with corresponding costs of supply.

(9) ACKNOWLEDGMENT

The author is indebted to the British Electrical and Allied Industries Research Association for permission to publish this paper.

(10) APPENDICES: SUPPLEMENTARY INFORMATION

(10.1) Lighting Load

By way of comparison Fig. 13 shows the disappearance of the residual lighting peak on a summer day when Double Summer

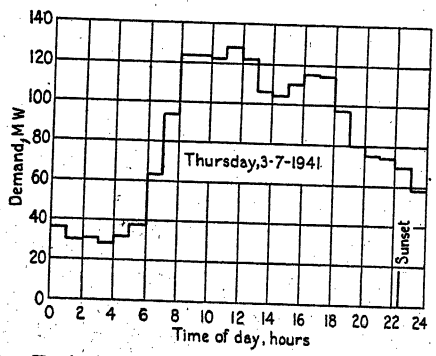


Fig. 13.—Typical load curve for a summer day with Double Summer Time in operation.

Time was operative. The effect of the later sunset is here accentuated by the blackout.

(10.2) Cooking Load

Fig. 14(*a*) shows the daily load curves for Whit-Sunday (S_{48}) and Whit-Monday (m_{48}) in comparison, and separately the excess in demand, which is similar in character and magnitude to the corresponding Easter curve given in Fig. 14(*b*). The information provided has been referred to in Section 6.3.4.

(10.3) Space-Heating Load

The various forms of domestic space-heating load are due to appliances used in—

(*a*) Living-rooms:—

(i) As a principal source of heat throughout the whole cold season,

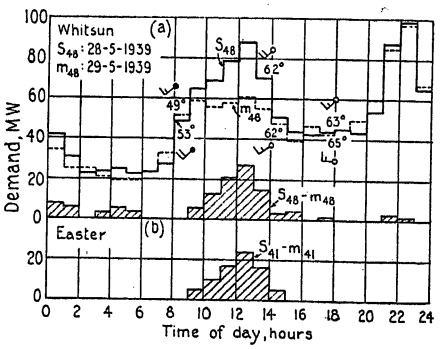


Fig. 14.—Difference in cooking demand on successive holidays.
(*a*) Whitsun. (*b*) Easter.

(ii) By way of supplement when the outdoor temperature is low,

(iii) Outside the periods in which solid-fuel fires are used.

(*b*) Bedrooms.

(*c*) Any other rooms, to prevent frost damage in severe weather.

Referring to Fig. 8(*a*), for instance, the load due to (*a*)(i) is represented by the area under the line "Regular space-heating demand"; that due to (*a*)(ii) by ripples such as G and J; that attributable to (*a*)(iii) by the big protuberances N, P, etc.; and the extra load due to (*c*) by the top two-thirds of the very large protuberance E. Bedroom heating (*b*) may have some part in the morning peak of the daily load curves given in Fig. 10, and is definitely responsible for the late-evening peak to be seen there.

For further elucidation Fig. 15(*a*) shows the differences between the load on a cold-snap day, t_{25}, an "ordinary" cold day, G_{27}, a mild winter day, w_{24}, and the basic-cum-lighting load curve as in Fig. 12.

In Fig. 15(*b, c, d*) the three stages of space-heating load, indicated in Fig. 15(*a*) by different shading, are reproduced separately, irregularities obviously due to variations in outdoor illumination

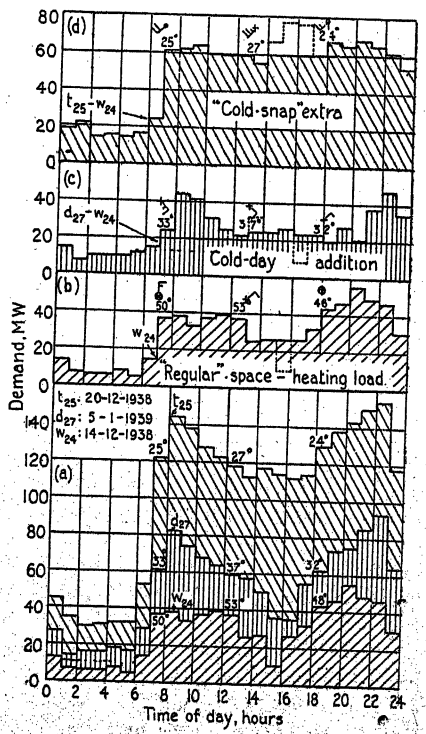


Fig. 15.—Winter space-heating.
(*a*) Demand on characteristic days.
(*b, c, d*) "Regular" demand and casual increments.

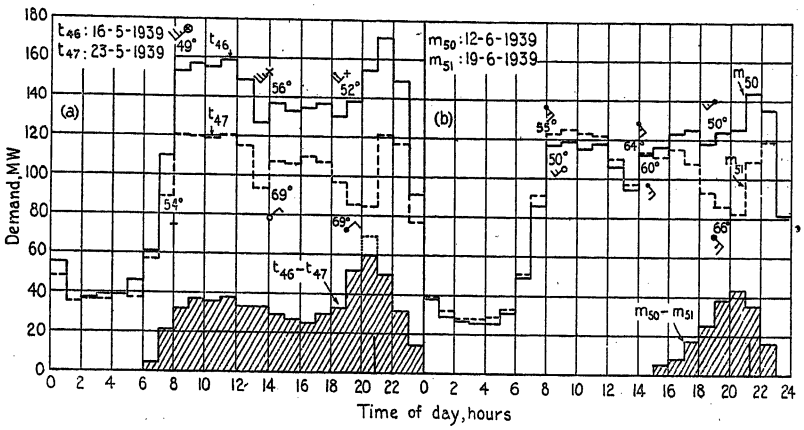


Fig. 16.—Post-winter space heating.
(*a*) Chilly May day. (*b*) Cool June evening.

being eliminated, i.e. only indicated by dotting. On the day w_{24} [Fig. 15(*b*)] the load was clearly of the type (*a*)(i) with a fairly constant forenoon level,* some drop in the early afternoon, and a "fireside" peak between 20 h and 21 h. The cold day d_{27} [Fig. 15(*c*)] brought morning and late-evening peaks, the former of (*a*)(iii) and the latter of (*b*) origin; and an all-day addition attributable to (*a*)(ii). The large extra demand on the cold-snap day t_{25} [Fig. 15(*d*)] was nearly constant throughout the hours of human activity; in the symbols introduced above it may be classified (*a*)(ii) and (*c*).

The kind of space-heating load classified as (*a*)(iii) is further illustrated by Fig. 16. Section (*a*) demonstrates the existence of a sustained all-day demand on a rather chilly May day, with a maximum of about 60 MW between 20 h and 21 h. This value had to be estimated, since the actual difference, shown dotted, seems to contain some lighting demand due to a difference in outdoor illumination. From section (*b*) of Fig. 16 can be seen the building-up and dying-down of the "fireside" load accompanying a cool evening in June; the m.d. again occurs between 20 h and 21 h. Note also the general similarity to the bottom curve in Fig. 15(*a*), and the fact that while the "regular" type of space-heating demand had a maximum of about 50 MW, the casual demand on a cold-snap day reached something like 150 MW.

Fig. 17 is developed from Fig. 7(*a*) by plotting the difference between the individual values of total demand and corresponding basic demand against outdoor temperature. Each point also indicates the corresponding weather conditions, but for convenience only the force of the wind is given, all arrows being arranged horizontally. The straight line is derived by calculating the most probable straight-line equation. It intersects the *x*-axis at about 65° F, which may be called the "basic temperature." The linear relation between temperature and demand is obvious. Force of wind seems to have relatively little bearing. Some of the scattering may be attributed to variations in lighting demand, although at midday the potential demand from this source is relatively small. The form of representation adopted may prove useful in future investigations into the characteristics of the space-heating load.

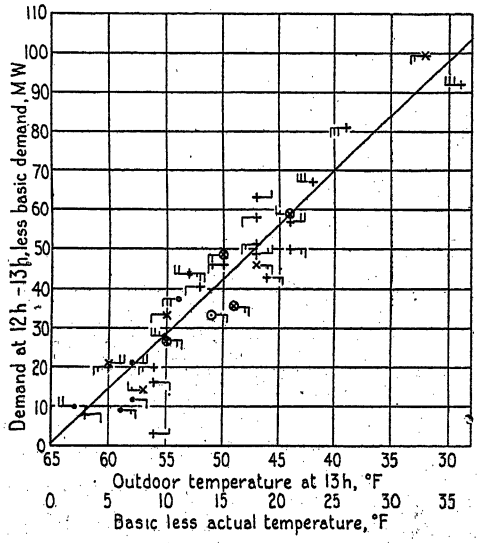


Fig. 17.—Sunday-midday space-heating demand as a function of outdoor temperature.

* It must be borne in mind that there is a certain proportion of commercial and space-heating load.

DISCUSSION BEFORE THE INSTITUTION, 16TH MARCH, 1944

Mr. W. N. C. Clinch: The paper is of particular interest. The information collected by the author naturally relates mainly to pre-war days, yet he gives useful pointers for ascertaining different potential load demands under different conditions. In several respects, however, I think that the author's hypothesis is somewhat questionable. For instance, in Section 3 he refers to the "higher level of income." It is difficult for a technical expert to define a level of income; I suggest that what the author means is a higher level of revenue.

Since the author's three-dimensional models were prepared, a change has been made in that loads are now taken half-hourly instead of hourly; this produces a very interesting change in the shape of the curves in the paper, in which again some hypothesis is involved. I should like to refer the author to a paper at the 1935 National Convention on Domestic Electrical Development, where the actual loads in certain areas were taken; there was then no question of hypothesis, because the curves were the true load curves for different areas under different conditions.

On the question of seasonal supply, it is very difficult to relate temperature alone to the demand for space-heating. I have known an instance where with the same temperature there was a difference in load of 30 000 kW, owing, first, to the psychological

effect of sunshine in the one case, and, secondly, to a difference in the relative humidity, namely 79% and 48% respectively.

Another interesting point is that the author has taken the connected load into account. I cannot understand how anyone can say honestly what the connected load on any electrical system is. The consumer can buy whatever apparatus he wishes and from numerous shops without record, so that the statistics of connected load have no true bearing on the load which is connected. For example, it is assumed that there are 60 000 to 100 000 kettles, which can be represented as equivalent to 100 000 kW of load, if there is no diversity and all kettles are of 1 kW loading. One wonders how far it is possible to go when so many hypotheses are made. Regarding water-heating it is not correct to refer merely to water-heaters, because they have different ratings and may be thermostatically controlled or otherwise, so that the effect of water-heating as such is itself a hypothesis and it seems dangerous to make any assumptions regarding it.

There is also the difficulty of assuming what effects wireless receivers have on the load. I think the Central Electricity Board is aware of the peculiar effect produced by particular artistes broadcasting at certain times.

In Section 8 the author refers to his "after-diversity maximum demand." I think we ought to ask the British Standards Institution to give us a more compact term to take its place. He assumes that the cooker load comes on while the industrial load is low, but that is not so.

If the load were to be developed to the extent the author has suggested, it would apparently be necessary to allow, on his figure of 0·9 kW per cooker, the connection of nearly 100 000 more cookers. The shape of the Sunday curve, in particular, would then be out of proportion (although he does not say so) with the weekday peak load, and that in itself is a problem which should be considered. It is a question, therefore, of developing other uses of electricity which in themselves can be controlled, so that such very high peaks, whether due to cooker load or to water-heating load, or to any load which has a characteristic which may in itself become high, can be themselves controlled.

It is, of course, very difficult to overstress the space-heating load. The potential space-heating load is a very real problem and has to be faced throughout the supply industry. This aspect of the matter must be borne in mind. A switch is a very simple device, and by use can give comfort without any bother in providing it; therefore the time must come when the author's curves change their shape and he must reconsider his deductions in the light of the future and not of the past.

Mr. D. J. Bolton: It is unfortunate that losses are included in the author's calculations and then, with great trouble and expense, are extracted again later. A second misfortune is the use of hourly instead of half-hourly readings. When the load is changing rapidly, e.g. at about 8 a.m., much closer readings are essential for any accurate plotting of the load curve. One can see what a different shape the curve might have followed had the hourly readings been taken at 8.30 and 9.30 a.m., instead of at 8 and 9. This element of fortuity could have been reduced to about one-third, if half-hourly instead of hourly readings had been taken.

The author has employed the very ingenious device of taking a cross-section so as to get a third dimension, which he uses to build up a three-dimensional load model. The deductions made, however, rest on several rather important assumptions, and in particular on the assumption that what he calls the basic load is entirely due to certain specific loads which are constant throughout the year at particular hours of the day.

That is one interpretation of the basic line, but another and equally valid interpretation is that it is made up, in part at least, of two or more complementary loads. I do not see any method in the author's technique for separating these two sources, both of which produce a certain amount of level, so-called basic effect. In other words, the effect of a summer load, if such a load existed, would be to obscure the corresponding amount of winter load, and the two together would produce a straight line. Starting with this straight line and analysing backwards by the author's method, there would be no means of discovering whether the line was due to one persistent load or to two or more complementary loads. The footnote to Section 5 does not seem to recognize this state of affairs adequately.

Doubtless the author has sound reasons for assuming that in the particular case he analyses there is no such seasonal summer load, but if his method is to be extended and used elsewhere, as it doubtless will be, I think consideration should be given to certain specific summer loads, such as refrigeration, air-conditioning, and some rural loads. There are also the "sponsored" summer loads, such as that due to immersion heaters grafted on to coal-fired boiler systems and encouraged by the 3-units-a-penny-in-the-summer type of tariff. The only way out of the impasse which I can suggest is that more should be measured and less left to conjecture. As many measurements as possible should be carried out, and the residue then analysed by the author's method. This would leave a much smaller margin for conjectural error.

In Section 10 more could be done by the method of differences, as by plotting the difference in a particular area between, say, the average Wednesday load and the average Thursday load when one of those days is an early-closing day.

Mr. C. J. O. Garrard: As the wealth of this country depends entirely on our fuel resources, conservation is extremely important. True economy in the use of coal and in the building of power plant can be obtained only by national planning based on a thorough knowledge of the load and its variations. This paper is valuable for the way in which it shows some of the difficulties which may arise if load development is not based upon accurate knowledge and is not directed towards rational ends. Thus electrical space-heating is certainly very convenient for the householder and may be very economical from his point of view. Supply authorities have in the past regarded it as a lucrative load, which they have done their best to develop. But the author shows that in the system he investigated, the use of electricity for space-heating during a cold snap, while it increased the units sold in the year by less than 1%, yet increased the maximum demand by over 18%.

As the normal maximum demands for lighting and space-heating are 85 and 100 MW respectively, while the maximum demand per consumer for lighting is unlikely to exceed 500 watts as compared with the kilowatt rating of the usual small electric fire, one may infer that somewhat less than 50% of consumers used electric heating at all and most of them only on a small scale. This estimate may be checked by considering that a maximum demand of 100 MW represents, say, 100 000 fires each of 1 kW, while the number of consumers is 384 000.

It follows that if the country-wide campaigns in favour of electric space-heating had been, say, twice as successful as they have in fact been, the difficulties of meeting the peaks in the recent cold spells might have been much increased, or alternatively, had there been no war, and had additional plant been installed to meet the increased peaks, a considerable capital expenditure would have been incurred for comparatively little return, regarded either from the point of view of the undertaking or of the public generally.

From the load curve of my own house it seems quite likely that a successful cooker campaign might increase the morning 8–9 hr peak, which is already troublesome owing not only to its

magnitude, but also to the rate at which the load increases between 7 and 9 o'clock.

Other factors which will tend to aggravate the peaks are the demand for speed, and thus of high loading, in domestic apparatus and the reduction of working hours which we hope will take place in the not-too-distant future.

Mr. J. I. Bernard: The author's paper presents an original line of research obviously of very great interest to the supply industry. But I feel that he has dealt with a little too much detail and has drawn wider conclusions than the data and possible sources of error in the method used will justify. If the paper had been confined to a somewhat clearer exposition of the methods which should be adopted in an analysis of load curves, it would have been more helpful to others wishing to make such an analysis; it would then not have laid such emphasis on the conclusions which relate to pre-war conditions and which may vary very much in the future.

In Table 9, the load factor of the industrial load is given as 45%, or 40% in a cold-snap year. This is very much higher than one usually associates with the industrial power load, and I am wondering what the possible margin of error might be. Will the author throw some light on this point?

Like Mr. Bolton, I am concerned that the author has made no reference to the possibility of electricity being used for water-heating only in summer, since of ordinary domestic loads, water-heating is one of the most popular and frequent summer uses of electricity. Mr. Garrard mentioned the possibility of improving the load factor of individual consumers. Recently I examined the records kept by one domestic consumer who, in the interests of fuel economy, took weekly readings in a house where electricity was used for some space-heating in winter, but as the sole source of water-heating in summer. He found the consumption of electricity in the whole house was definitely higher in summer than in winter; in other words, the water-heater used for summer water-heating is the best counter-balancing load that we can find to the electric fire.

Mr. G. O. McLean: This paper is an analysis of a particular undertaking's load several years ago. I use the word "particular" to draw attention to the danger of applying the author's conclusions and results, as far as load factors go, to the general case. It is nevertheless an excellent example of how load can be dissected; but speaking as a practical supply engineer, I feel that the ordinary, straightforward method of comparing one, two or three pairs of chosen daily load curves will give similar results to the author's.

The author has described and exhibited a load model. I did something on these lines many years ago, and my experience is that the contour plan is much easier to construct, easier to store and move, and much better than the load model. An example of the procedure may be of interest.

Fig. A shows the contour plan for half a year of a small suburban load, wholly residential. We start with ordinary squared paper, divided up into hours along one axis and days along the other, in the same way as the base of the author's model, but instead of cutting out cards each little thin rectangle, representing one day, is coloured* according to the load for each half-hour portion. I have merely split up the total load into 6 gradations of 200 kW each, but of course these can be increased to any number desired. Once a week, or daily if desired, the contours or edges of the colours are joined up, to obtain the effect shown, which very clearly brings out the valleys and the peak loads. This is a very rough example, but it shows the characteristics and trends of the load, e.g. the very prominent effect of Sundays.

Fig. B compares two daily load curves (winter and summer

* A coloured slide was shown at the meeting.

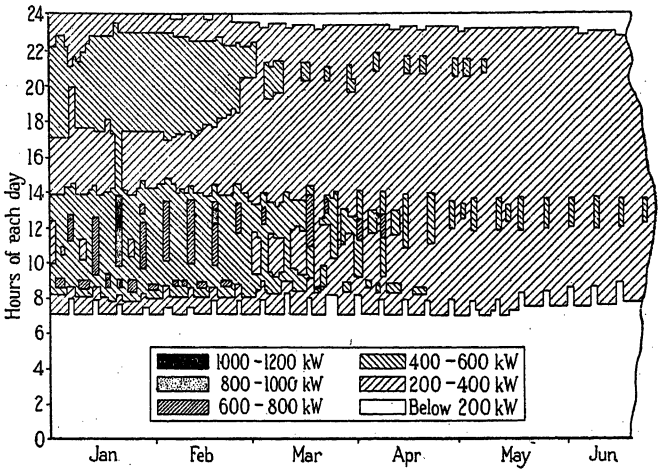


Fig. A.—1940 load contours.

Sundays) and shows how they can be used. This is admittedly the simplest case, where only two daily load curves are necessary to break up the load curve into its components. The basic load runs right through as the minimum load and is known from the daily readings to vary from 30 to 130 kW. The lighting load

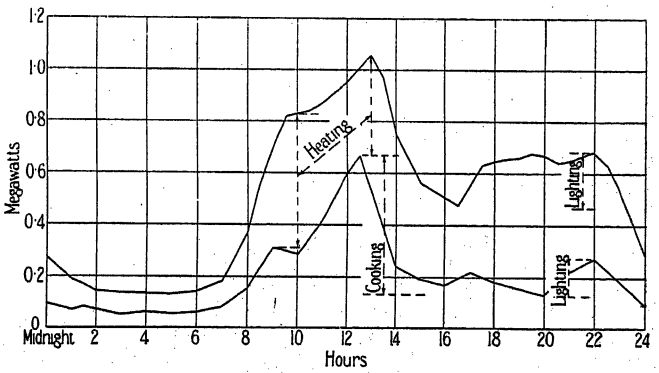


Fig. B.—Residental load. January and June, 1940. 1 700 consumers.

and its duration of about 2 hours in summer and 6 hours in winter is very clearly shown during the evening hours. The cooking load is also shown on the summer curve, while the remainder on the winter curve is heating.

Fig. C gives the load factors for this residential suburb compared with the author's results for the Northmet Power Co. in the middle column. Allowing for the fact that the Northmet has 420 000 consumers and this residential suburb 1 700 consumers with no industrial load, the results are seen to be quite comparable. The "total supply" load factor is a little lower for the

Fig. C

Load	Load factors—per cent.	
	Northmet	Residential suburb
Total supply	33 (39½*)	29
Lighting	15 (18½*)	17
Space-heating	13 (20*)	18
Domestic cooking ..	35 (31½†)	16
Basic supply	63	55

* Excluding cold snaps. † On own peak.

suburb, as one would expect. Lighting is very much the same (17 compared with 15–18½), and space-heating is also more or less the same; the big difference is on domestic cooking, and is, I feel, due as much to the different saturations as to the diversity of occupation and habits of the consumers. In the author's case, the cooker saturation was 11%, while in this residential suburb it is 22%. I think that Fig. C shows that my word of caution regarding drawing general conclusions from the particular is justified.

I agree with the author's view on the importance of after-diversity demand. In this suburb after-diversity demand per consumer is 0·65 kW; the cooker A.D. demand is 1·7 kW, and the space-heating A.D. demand as low as 0·3 kW per kW connected.

Mr. B. Wood: After the cold winters of 1940 and 1941 many articles in the Press endeavoured to show the phenomenal effect of space-heating in forcing up the peak. It is perhaps generally forgotten that the same thing occurred in 1929, only in a lesser degree, owing to the smaller number of electric fires then installed. I believe that cold winters occur in roughly an 11-year cycle: following very closely the sunspot cycle, possibly with a slight lag. The really hard winters of the last 50 years fit into this cycle, the most severe in 1895, another in 1917 (22 years later), the next in 1929 (12 years later), and then the two winters of 1940 and 1941.

The interest, I presume, in the study of load curves is to know what to do and to take appropriate action. Short of preventing consumers putting on electric fires at a particular time or inducing them not to do so, the only remedy seems to be to provide sufficient plant, which might appear to involve prohibitive capital cost, although if it only means putting the plant programme forward a few years this is not so serious.

The sunspot-cycle hypothesis was brought to the notice of the Electricity Commissioners in 1929, and an investigation was made by the Meteorological Office, who doubted whether the thermometer readings disclosed any such cycle. However, an ordinary thermometer in an enclosure is not a satisfactory guide to conditions within a building; its time of response is too small. Hence, minimum readings are not a reliable indication. Other criteria, such as the number of days during which the temperature never rose above 32° F, may also be misleading, since it is characteristic of settled cold weather that there may be bright sunlight during the day.

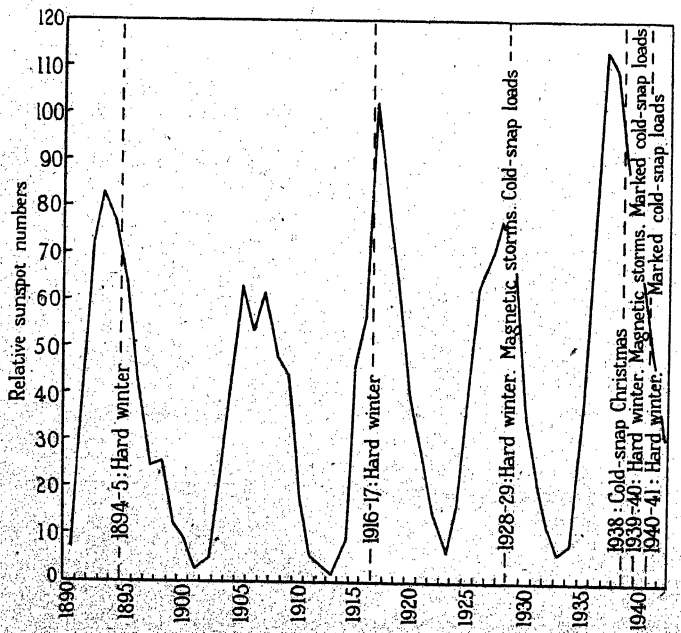


Fig. D.—Relative sunspot numbers and hard winters.

(*Communicated*): The curve in Fig. D gives relative sunspot numbers over the period of interest. The notable winters for outdoor skating are indicated. It will be seen that trouble may be anticipated around 1951. It must not be inferred that cold days do not occur in other winters. A study of the cold-winter cycle can only suggest when the likelihood is greatest. Similarly, the date of a cold snap must be regarded as largely fortuitous. The cold spell in December, 1938, was troublesome not by reason of its intensity, but because it fell just before Christmas at the time of normal system peak. The normal cold snap in early February (Buchan's first cold period) is less troublesome.

Mr. E. A. Logan: It appears to me that the paper is a means to an end; a tool not a finished product. It serves to outline a method of separating the various types of load which go to make up the demand, and illustrates one point in particular, namely the high level of the demand due to the space-heating load. The question arises whether space-heating load is really lucrative and the paper seems to suggest that it is not. As a supply engineer, I would not like to part with the space-heating load. Therefore, while I cannot suggest a reasoned answer, I feel that this conclusion drawn from the paper is erroneous.

The paper should furnish the raw material for further papers on tariffs and speculations whether individual items are remunerative for electricity undertakings. A further speculation is that, given a relation between temperature and variation from basic load (which the paper provides), it remains for the Meteorological Office to supply to undertakings forecasts of the weather conditions 12 months hence to enable load forecasts to be more closely related to fact. Until, however, the science of meteorology becomes so far advanced, the technique of the present paper remains analytical instead of synthetic.

Mr. E. E. Jolly: On a first reading the paper is rather frightening to a supply engineer, especially when one thinks of the potential space-heating developments in the post-war era. The author apparently attempts to calculate the consumer charge after applying the consumer diversity. The present basis of the charge is a two-part tariff, and therefore the author has a perfect right to give us these curves and also the peak-load period, that is, the effect on the undertaking's demand. From that we can derive the consumer charge, after applying the consumer diversity.

In the early days our tariffs were more or less scientific, and a higher price for lighting than for power was justified. The author suggests that tariffs should be on a scientific basis, but latterly I think most people will agree that undertakings have been getting what the consumer will pay. There is no question of a consumer charge being brought in at all; it is simply a question of what we can get for the type of load. That, in my view, is wrong, but I do not see how it can be amended until the basis of charge to undertakers for bulk supply on the two-part tariff system is amended.

I am not so concerned about the space-heating demand, and I have great hopes for it in the post-war years, because generally speaking most people with electric fires are at present using them as a luxury. We have not got down to the everyday consumer with a fire. The education of the public will be not to use their electric fires so much in the winter, but to use a coal fire, and to use an electric fire when we want it used, i.e. in the spring, summer and autumn. The curve will be altered very much after the war, and will also change according to the situation of the various undertakings. Half-an-hour out of London the demand is quite different from that in London; nine miles out of London it comes a quarter of an hour after the industrial peak, but in London it is right on it. In co-operation with the C.E.B.,

I think we can overcome the space-heating problem of the future.

Mr. H. A. P. Caddell (*communicated*): The "cold snap" peak at t25–w25 at 8–9 h, due apparently to a few degrees of frost, is a most disturbing phenomenon. Apart from the unhappy facility of electricity as a secondary heating agent, perhaps the reason for this is that so few of us are lucky enough to live in thermally efficient houses. It would be interesting to know if the author has been able to make any estimate of the A.D.D. per kW of domestic heating connected. Presumably, the average connected heating load per consumer would not be less than 1–1·5 kW in this area. From Fig. 12 and allowing 20% for non-domestic uses, the A.D.D. per kW connected appears on this basis to be between 0·23 and 0·34 kW for w25 and between 0·14 and 0·21 kW for f27. These figures agree reasonably with those quoted in a recent paper and with my own experience.

With regard to cooking, some years ago I tried to get figures relating to the Sunday midday peak, using the method described by the author. The resulting A.D.M.D. figures per cooker over three consecutive years showed close correspondence and were substantially the same as those the author gives, though slightly higher. With regard to the cooker A.D.D. at 8–9 h, is any further information available in making the estimate of 0·2 kW? Based on an average consumption of 1 500 units per cooker per year, and assuming the system maximum demand was at 8–9 h, this figure gives a load factor on the generating plant of 86%, which is surprisingly high. My experience of loads with relatively higher cooker saturation suggests a figure of about 0·4 kW, with the weekday 12–13 h A.D.D. about 50% higher, this latter agreeing with the author's figure.

The generally low saturation and consequent relative insignificance of water-heating makes it difficult to estimate this factor. My experience with thermostatically-controlled immersion heaters suggests an 8–9 h weekday A.D.D. per unit agreeing approximately with that used by the author, but there are indications of an appreciably higher figure at Sunday midday.

With regard to the load factor of the domestic load, for average appliance saturations and excluding cold-snap conditions, my experience agrees with the figure of about 30%. With higher cooker and water-heater saturation, the load factor referred to 8–9 h weekday A.D.D., and consequently on the generating plant (assuming the system M.D. still remains at 8–9 h weekday) may approach 35–40%. In such cases, however, the load at Sunday midday may considerably exceed that at 8–9 h on weekdays and the load factor, referred to A.D.M.D. and consequently on the local distribution plant, may fall to little over 20%. This would seem to follow from the fact that with an average consumption per cooker of 1 500 units per year and an A.D.M.D. per cooker of 0·9 kW, the load factor of the cooking load on the local distribution plant is only 19%. This brings to mind the question of what proportion of distribution costs are related to maximum demand.

Regarding the author's proposals for further research by recording the component loads, it appears that in a reasonably compact distribution with overhead conductors the various components, i.e. cooking, water-heating, and lighting plus heating plus miscellaneous, could be supplied from separate phases without causing appreciable out-of-balance difficulties, and merely by the addition of service wires and meters where necessary. This method, if practicable and if officially approved, would have the advantages of cheapness and of giving early results.

In conclusion, I would like to support the author's plea for the scientific development of bases for calculating and comparing costs of supply and would further suggest the need for dealing with the "value of service" factor as far as possible in the same manner.

Mr. E. W. Dorey (*communicated*): During the war the advance in industrial lighting has been considerable and the degree of illumination required to-day is far in advance of that on which the author's data are based. The maximum demand for lighting factories, etc., is now a far greater proportion of the total load and will undoubtedly substantially reduce the load factor of the industrial power load, which for the Northmet Power Co. is assessed at the unusually high figure of 45%. I think that some current restrictive tariffs which limit the amount of lighting load available at power rates will have to be considerably modified to meet present illumination requirements and that a comprehensive industrial tariff should be available without any restriction as to use of lighting supply.

The industrial load factor of the Northmet is no doubt partly due to the operation of an off-peak load tariff. It is regrettable that so many supply authorities refuse to offer off-peak terms, as some consumers can take full advantage of these terms, thereby conserving the capital of the supply authority and assisting in fuel economy by reducing the amount of relatively inefficient generating plant which has to be run to deal with the Grid peaks. Some supply authorities argue that under no conditions would they permit their average price from the consumer to fall below a certain datum figure, i.e., if this datum figure were obtained with a winter peak-load factor of, say, 50%, then if the consumer could by reducing the demand improve the load factor to 75% no rebate whatsoever would be granted. So long as this attitude rules there is no possibility of taking full advantage of clipping the peak.

The curves and other data in the paper make it abundantly clear that the space-heating peak demand is a most serious factor and is quite uncontrollable. I should have expected supply authorities to welcome off-peak tariffs with loads which can be controlled, and particularly so in war-time when peak-load restriction is in the national interest.

If the demand curves for the space-heating load of the Northmet are typical of other supply authorities, this class of supply cannot apparently be profitable to the undertaking and must seriously enhance the total cost of supply, particularly to meet the "cold snap" demand. On the Northmet domestic two-part tariff the running charge per unit is 0·625d., and the coal clause addition to industrial users at the beginning of this year was 0·284d., which leaves 0·341d. The most favourable load factor (excluding cold snap) is 20%. Power users pay approximately 90s. per kW per annum, and this on a load factor of 20% is 0·62d.; in addition they pay 0·4d. per unit plus coal clause for the first 50 000 units per month, so that by comparison we have for a power user with 20% load factor and consumption at 50 000 units per month: M.D. charge, 0·62d.; unit charge, 0·4d.; present coal clause addition, 0·284d., a total of 1·304d., while the space-heating user pays 0·625d., a difference of 0·679d. Diversity factor of space-heating load has no bearing as the charge is virtually a flat rate of 0·625d., irrespective of load factor. Similar terms are available in most supply areas and the load conditions are doubtless comparable, and one is led to enquire how such a load can possibly be profitable to the supply authority.

Mr. R. B. Rowson (*communicated*): It is to be hoped that the results shown by the paper will impress those who still doubt the necessity of analysing system-load curves and who often base their arguments on the hypothesis that the domestic load has infinite diversity. The Northmet Power Co. also deserve the thanks of the whole supply industry for allowing such a grim warning to be made generally available.

One of the principal points is that these very high demands occurred on a system on which, judging from the number of cookers, etc., only a small percentage of the total number of

consumers availed themselves of the full service in spite of the relatively low charges in force. Even so, the domestic demand due to heating quite overshadows any of the other loads, and if all the 240 000 all-in tariff consumers took advantage of the facilities offered, the position would be impossible. This is illustrated by a curve* for 40 all-electric houses, the peak being 440 kW at 8 h.

The practical consequence of the analysis is the question whether the two-part domestic tariff has not outlived its usefulness. The tariff places no restriction on use, gives no encouragement to the consumer to keep off the peak, and neglects installed loading or maximum demand in its fixed charge. Clearly, as now fixed, the revenue such a tariff will produce is usually inadequate to meet anything like full domestic electrification, unless the unit rate is impossibly high.

* PUTNAM, H. V., and DANN, W. M.: "Loading Transformers by Copper Temperature," *Electrical Engineering*, 1939, 58, discussion, p. 511.

At the time the records were made it seems from Section 7 that a large part of the fixed charges of, say, 90% of the consumers was being used to subsidize a supply at less than cost to the 5 or 10% who used the facility for heating.

As regards future work in this direction, the relationship between temperature and load is clearly established by the method of analysis employed. Similar tests with consumers charged at higher tariffs might show whether a sufficiently high price inhibits the heating load altogether or merely results in the undertaker being left with the "cold-snap extra."

The cooking load in this country also requires further analysis. In particular, many engineers will feel that the estimate of 0·2 kW as the A.D.D. at 8–9 h is low for the winter though it might be reasonable in summer months. The correctness of this result can only be proved by further tests, and I hope that the author will be able to indicate that the recent E.R.A. questionnaire has borne fruit and that tests are under way.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. P. Schiller (*in reply*): The purpose of the paper has been to apply the scientific method to a field which hitherto abounded with tags and conjectures. Particular care has been taken to state facts only, and to avoid inferences. For example, in stating values of load factor, no implication is made as to the economic significance of load factor, for this depends on the proportion of truly demand-related cost in the total cost of supply, which is a feature still awaiting systematic elucidation. Any challenge of a statement made in the paper ought to have been accompanied by a proof on the same lines as applied in the paper, the latter having been deliberately presented in great detail to enable such a course to be taken.

Mr. Clinch objects to the expression "higher level of income." What is meant is "higher economic status," not "higher level of revenue." As to the relationship between the demand for space-heating and other factors, the only reliable basis of argument is that of statistical correlation, as applied in Fig. 17.

Connected load—or rather installed load, according to B.S. terminology—has been taken into account only in regard to such appliances as are ordinarily hired out by the supply undertaking: cookers, washboilers and water-heaters. I cannot trace any other reference to installed load, particularly with regard to kettles. It would be of considerable interest to compare the results of load analysis with the corresponding installed loads. In view of the impracticability of keeping up-to-date records as to the installed load of each domestic consumer, the methods of statistics can be employed for sampling. This has been under consideration by the E.R.A. for some time, and positive developments may be expected soon.

In reply to Mr. Bolton, the use of load records based on hourly mean loads and including station-auxiliaries demand was forced upon me by the existing material. I am glad to note that the procedure has now been changed in that only the energy sent out is considered, and that the demand is recorded half-hourly. I agree that the existence of specific summer loads would make it more difficult to separate "basic demands." In the present case, however, such loads were insignificant. Even if it were assumed that all the water-heaters installed had been operating during the summer months only, this would involve an error of only a few per cent. The "method of differences" is implied in Figs. 2, 5, 6, 7, 8, 14, 15, and 16.

Mr. Garrard stresses the trend towards deteriorating load factors inherent in the conventionally developed domestic load. The load factor of the industrial load, which Mr. Bernard questions, "does not consider seasonal extra demand due to lighting and heating at the power rate" (p. 442). Besides, it is based on 1-hour demand.

I doubt Mr. McLean's statement that "comparing one, two or three pairs of chosen daily load curves will give similar results" to those obtained by me. While this procedure forms part of my method (cf. Fig. 8), it is supplemented by the analysis of seasonal demand curves. At best it yields demand values only, and if in the past the corresponding consumptions were estimated, the basis used has been in the nature of a wild guess. In fact, anything can be proved in this way: it is the ideal way of substantiating wishful thinking.

The reference to contour plans (or load maps) as being superior to three-dimensional load models does not appear apposite, since I was not dealing with methods of load representation but with load analysis; for the latter purpose the utility of the load model is unsurpassed. How convenient to choose and compare pairs of suitable load cut-outs. I may add, however, that a draft of an illustrated E.R.A. report on methods of load representation, including load maps, was prepared over a year ago, and will be issued after some practical trials have been completed.

Mr. Wood's reference to the apparent relation between sunspot frequency and hard winters is of interest. If absolutely reliable long-term forecasts of this kind could be established, considerable economic advantages could be achieved. Of equal importance, however, would be the negative assurance that no cold snaps of serious importance were to be expected in the intervals.

In reply to Mr. Logan, the paper gives some data in respect of the space-heating load on the system in question, but does not express an opinion as to whether this load is lucrative.

Mr. Jolly's reference to tariffs is not quite clear to me, since in the paper the question of tariffs is not touched.

I appreciate the pertinence of Mr. Caddell's contribution. Regarding installed heating load I would refer to my reply to Mr. Clinch. The E.R.A. has instituted research into the after-diversity demand of the principal components of the domestic load, and a report will be forthcoming in due course.

Mr. Dorey enlarges on the subject of tariffs, but since this was excluded from the ambit of the present paper I have to refrain from making a reply.

Mr. Rowson's support of scientific research is welcome, though I am unable in this place to follow him into the field of tariffs. In connection with the assumed cooking A.D.D. of 0·2 kW per consumer at 8–9 h, it must be borne in mind that this is an hourly mean value of a reputedly peaky load. More research on this point is in hand.

COPPER CONDUCTORS FOR OVERHEAD LINES*

By G. W. PRESTON† and H. G. TAYLOR, D.Sc.(Eng.),‡ Associate Members.

(*The paper was first received 9th November*, 1943, *and in revised form 2nd March*, 1944. *It was read before the* TRANSMISSION SECTION *12th April*, 1944.)

SUMMARY

Although the title of the paper refers only to copper conductors, copper-alloy and steel-reinforced copper conductors for use on overhead lines are included. The creep of conductors and their initial non-elastic extension are considered in relation to their effect on sags and their compensation by an increase in erection tension as an alternative to pre-stressing. A typical stress/strain curve for copper conductors is given.

Information on the annealing characteristics of hard-drawn copper and copper-alloy conductors is included, with special reference to the effects of impurities in the metal. Maximum safe operating temperatures for such conductors are discussed, together with maximum permissible current loadings.

Hollow copper conductors of various types for voltages up to 200–300 kV are described and some of their characteristics enumerated. The features of cadmium-copper conductors are dealt with in comparison with other types of high-tensile overhead conductor.

Steel-reinforced copper conductors receive special attention, particularly in regard to the protection from corrosion of the steel wires. Results of a long-time investigation are given in full, with conclusions and recommendations. Copper-clad steel wires, their characteristics and use as reinforcement in copper conductors, are discussed.

Details are given of developments in the application of compressed sleeve joints to copper and copper-alloy conductors. Suitable joints for cadmium-copper and steel-cored copper conductors are described and test results given.

(1) INTRODUCTION

A comprehensive paper on copper conductors for overhead lines would involve a history of overhead transmission covering more than half a century. Such a paper could not be written in present circumstances, and it is intended in the present contribution only to outline some recent developments in the use of copper as an overhead-line conductor material.

For low- and medium-voltage overhead construction copper conductors have found a very wide field of application. As a general rule span lengths are short, conductors are often not erected to their maximum permissible tension, and copper conductors are ideal for the purpose. For high-voltage distribution, copper, cadmium-copper and steel-reinforced copper are all used extensively, while for main long-span transmission and distribution lines, such as the Grid lines, the use of cadmium-copper and steel-reinforced copper is becoming more widespread.

For transmission lines operating at voltages up to 200–300 kV, special forms of hollow copper conductor have been employed to a considerable extent abroad, and these, together with the other types of conductor referred to above, are dealt with in the paper.

(2) HARD-DRAWN COPPER CONDUCTORS

The search for new materials or special methods of construction to meet particular engineering difficulties always results in greater publicity being given to, and more interest being shown in, the novelty than in the ordinary straightforward case. And so it is with overhead lines—special conductors for long spans, high river crossings, and lines operating at 100 kV and over tend to receive comparatively more attention than ordinary copper conductors, which are still used on probably 90 per cent of the normal construction. The proved efficiency and reliability of such conductors established by long experience leave little new to be said of them, and it is proposed to refer only to two matters upon which some information may be helpful, namely the non-elastic stretch of conductors and their maximum safe operating temperatures.

(2.1) Conductor Elongation

One of the several variables which help to make the design of overhead lines a less exact science than that of some other forms of structure is the elongation of a conductor under stress. That elongation is partly elastic and partly plastic, and it is often difficult to distinguish between the two effects, one giving a false impression of the other.

With sustained loading all metals tend to exhibit in varying degree some permanent extension which, when it takes place over long periods, is often termed "creep." The creep resistance of hard-drawn copper at normal temperatures is good. Phillips and Smith§ give the following results of creep tests on wires:—

Ultimate tensile strength	Stress applied, per cent of ultimate	Duration of test	Final creep rate, per cent per day
tons/in²		days	
32·6	47	32	<0·0008
32·6	75	32	0·0013
30·6	39	After 2	0·00011

Similar tests have been conducted by the British Non-Ferrous Metals Research Association on hard-drawn copper wire, 0·16 in dia., having a tensile strength of 27·5 tons/in². When this wire was loaded to 50% of its tensile strength the initial extension was 0·11%; 21 days later the total extension was 0·1175%. At 75% of the tensile strength the initial strain was practically complete after the first 10 days. Subsequently for 220 days there was an average strain rate of 0·00005% per day, after which there was no further extension for at least 100 days, when the test concluded after about a year with a total increase in length due to creep of about 0·01%—excluding the creep which took place in the first 10 days.

As these results show, when a wire is first loaded there is an initial non-elastic extension at a rate greater than the subsequent creep rate. When single wires are stranded together to form a conductor the initial elongation which takes place as internal stresses become balanced may be even more marked and may be of importance in overhead lines, since it tends to cause an increase in sag after erection. Pre-stressing of the conductor is one method of removing the initial non-elastic extension, but as an alternative the conductor may be over-strung at the time of erection by an amount sufficient to compensate for the extension that will occur when the maximum loading is eventually applied to it. A satisfactory method of determining the degree of over-stringing required is to ascertain by test the permanent extension that will occur in the conductor in any given span length as a result of the application of the maximum loading, and then to deduct an equal length from the length of the wire in the span when calculating the appropriate erection sag and tension, or

* Transmission Section paper.
† Copper Development Association.
‡ Formerly Copper Development Association.

§ *Proceedings of the American Society for Testing Materials*, 1936, 36, p. 263.

better still to employ in a graphic method of calculation, such as the Thomas chart, the actual stress/strain diagram obtained by test. By these means the sag at the time of erection will be less than would otherwise be the case, but it should increase to the correct value after a period in service if loads approximating to the maximum assumed are applied to it for any appreciable length of time.

The initial loading of a stranded conductor not only gives rise to non-elastic extension but it also causes the apparent modulus of elasticity to increase. It is the final or higher modulus that is normally used in sag calculations. For copper conductors this is usually assumed to be 18×10^6 lb/in^2. The apparent initial modulus up to, say, 20–25% of the ultimate tensile strength would, however, be lower than this, say of the order of $14{\cdot}5 \times 10^6$ to 15×10^6 lb/in^2. To be accurate, it is this lower modulus which should be used in the calculation of erection curves for unstretched conductor, although all curves relating to the final behaviour of the conductor after loading should of course be based on the higher modulus.

In determining the initial elongation of a conductor by test it is not necessary to maintain the loading for long periods, since the major portion of the extension takes place in the first hour or two. Test loads need be maintained, therefore, only for limited periods ranging from, say, 15 minutes at 25% of the ultimate to 2–3 hours at 80%.

A typical stress/strain curve obtained in this way is shown in Fig. 1. The curve relates to a conductor composed of two

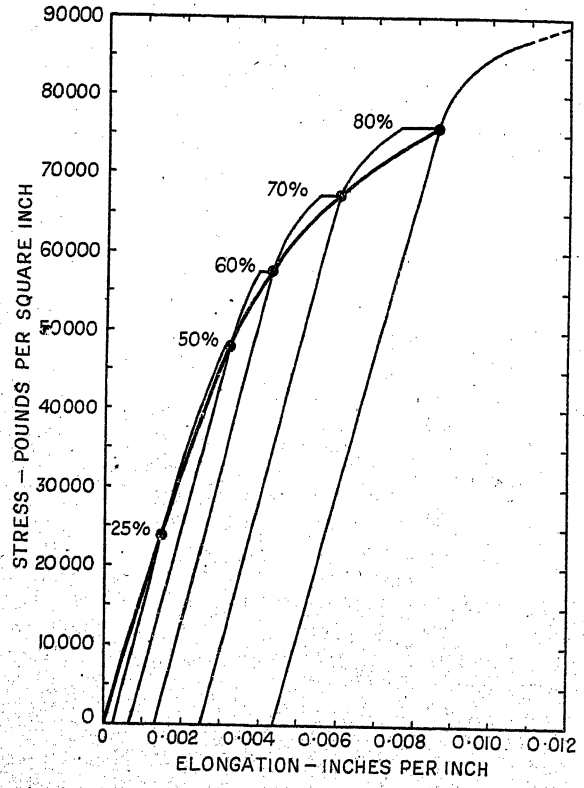


Fig. 1.—Typical conductor stress/strain diagram with sustained loading.

0·107 in dia. hard-drawn copper wires and one 0·107 in copper-clad steel wire. The nominal breaking strength of the conductor was 96 000 lb/in^2, although the actual ultimate stress on test proved to be about 100 000 lb/in^2.

From a number of such tests on different sizes of conductor a typical composite diagram can be drawn such as is shown in

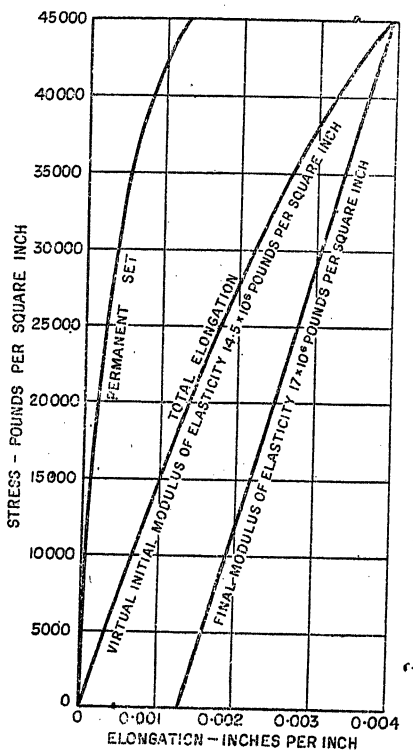


Fig. 2.—Typical stress/strain diagram for stranded hard-drawn copper conductors.

Fig. 2, which represents the combined results of 18 tests on stranded 7- and 19-wire hard-drawn copper conductors having a nominal ultimate tensile stress of about 59 000 lb (26·5 tons)/in^2. The same curves would also be approximately correct for single hard-drawn copper wires having a slightly higher nominal ultimate stress, and they may for practical purposes be taken as applying with sufficient accuracy to stranded hard-drawn copper conductors as covered by B.S. 125.

It will be noted that for a tensile stress equivalent to about half the ultimate, which is the assumed maximum for most lines in this country, the permanent extension which may be expected is slightly less than 0·04%. The virtual modulus on initial loading is shown in the curves as being about $14{\cdot}5 \times 10^6$ lb/in^2, and the ultimate modulus about 17×10^6 lb/in^2, though, as has already been pointed out, 18×10^6 is usually assumed.

To compensate for stretch, the reduction in sag at the time of erection, expressed as a percentage of the normal sag, will vary with span length and the size of conductor. For example, on the basis of the diagram in Fig. 2, at 60° F the reduction in sag of a 0·1 in^2 (7/·136 in) copper conductor in a 400-ft span would be about 13%, and in a 600-ft span about 7%. For a 0·15 in^2 (19/·101 in) conductor it would be about 9% in a 600-ft span.

(2.2) Maximum Permissible Operating Temperature

In the ordinary course of events the annealing of hard-drawn copper overhead-line conductors is not a factor which has to be taken into account. Line losses and considerations of voltage drop normally limit the current-carrying capacity of a line to a level much below that which could cause any rise in temperature likely to result in softening of hard-drawn copper, and except for an occasional bonfire or grass fire or other exceptional occurrence little trouble is experienced from this cause. There are occasions, however, when exceptionally heavy emergency overloads have to be carried, or, as has more recently

been the case, when other factors such as the necessity for adoption of the maximum possible current loading to economize in the consumption of copper have to be taken into account, and the possible loss of strength of a conductor due to annealing has to be considered.

Operating a line at an exceptionally high temperature not only has a bearing on the possible softening of the conductor metal but also has an important effect on ground clearances. In a new line these can of course be safeguarded, although perhaps at the cost of an uneconomical design. The only matter now under consideration, however, is the maximum current loading of hard-drawn copper conductors which can be allowed without danger of a serious loss of strength.

A good deal has been written about the annealing characteristics of copper, and some of the statements made have been rather too definite, having regard to the many variables involved. Impurities in the metal and the degree and rate of cold working applied to it all have an important bearing on the temperature at which it starts to soften and the rate at which it loses strength with time.

In general the more severely cold-worked is the metal, the lower is the softening temperature and the greater the rapidity with which it will anneal. Curves in Fig. 3 show the extent to

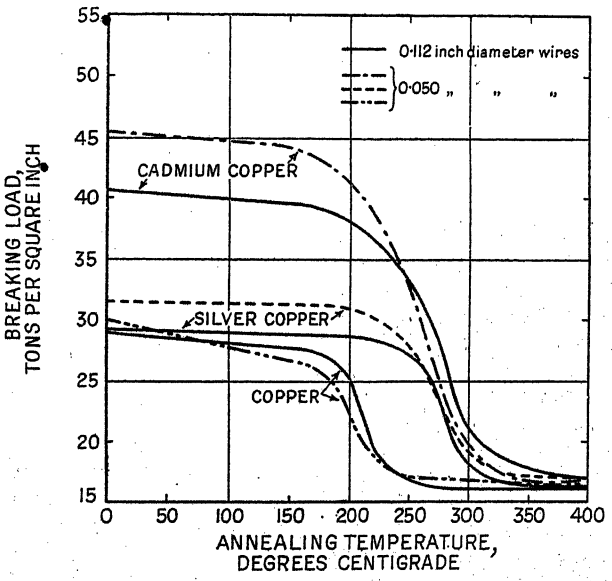


Fig. 3.—Tensile strength of 0·112 in and 0·05 in hard-drawn copper, cadmium-copper and silver-bearing copper wires after heating for 24 hours at various temperatures.

which normal-purity hard-drawn high-conductivity copper wires of diameters 0·05 in and 0·112 in were found to anneal when maintained for 24 hours at various temperatures. Corresponding curves for cadmium-copper wires are also shown. The addition of cadmium to copper has the effect of raising the temperature at which the hard-worked metal can be operated without softening. In this respect silver is also particularly effective, the addition of only about 0·08–0·1% having the effect of raising the annealing temperature by more than 100° C. For comparison, curves are included in Fig. 3 to show the relative annealing characteristics of 0·05 in and 0·112 in wires of hard-drawn copper containing about 0·1% of added silver.

Even very small quantities of some elements may have an appreciable effect on annealing, and Fig. 4 shows the approximate effect of small contents of silver on the loss of strength of hard-drawn 0·083 in wires of a given copper when subjected to a temperature of 275° C for 15 min. It will be noted that

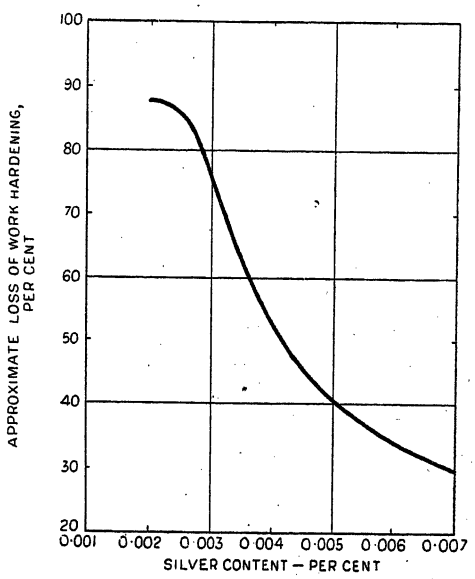


Fig. 4.—Degree of annealing of 0·083 in hard-drawn copper wires containing very small percentages of silver when heated for 15 min at 275° C.

the difference between, say, 0·002% and 0·004% silver is marked, yet such a range of silver content is possible in commercial high-conductivity copper, though for the most part silver would not exceed about 0·003%. Below about 0·002% the effect of silver would appear to be relatively unimportant.

Slight variations of oxygen content do not have any marked effect on annealing, but the reduction of the oxygen to very low limits has a considerable effect in retarding it.

The effect of silver, oxygen and other impurities on the long-time annealing characteristics of some hard-drawn 0·066 in dia. copper wires is illustrated in Fig. 5. Curves (*a*), (*c*) and (*d*) have

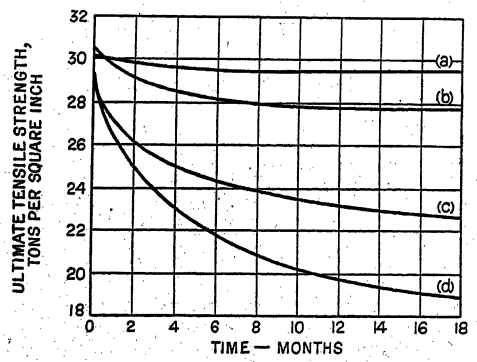


Fig. 5.—Loss of tensile strength of 0·066 in hard-drawn wires of various commercial high-conductivity coppers when maintained at 80° C for long periods.

Impurity contents, per cent:—

	(*a*)	(*b*)	(*c*)	(*d*)
Oxygen	0·0001	0·05	0·019	0·03
Silver and gold	0·0017	0·003	0·001	0·00006
Approx. total of other metallic impurities	0·0065	0·015	0·0061	0·005

been drawn from results obtained by Voce.* The effect of a very low oxygen content will be seen in curve (*a*). A similar effect would also be produced with normal oxygen present if silver were added to the copper.

All the above data refer to softening under maintained high-temperature conditions and were determined on unstressed material. In practice, at least so far as overhead-line conductors

* *Journal of the Institute of Metals* 1941, 67 p. 1.

are concerned, the copper would be heated while under an appreciable tensile stress, in which condition its annealing characteristics might not be the same as those determined in the unstressed condition. Furthermore, in practice sustained high temperatures seldom occur, maximum temperature conditions being attained only intermittently. Unfortunately there is little information on the effects of intermittent heating, and it cannot be stated with certainty whether the effect of such heating is directly cumulative, as it probably is, or whether under certain conditions there is some form of partial recovery. No definite ruling, therefore, can be given, and on balance it would seem advisable to adhere in practice to a temperature of 80° C as being a reasonable maximum for long periods, if any detrimental softening of the metal is to be avoided.

(2.3) Current Loading

Since conditions in the open air are very variable, the current that will, under service conditions, give rise to a temperature of 80° C in a conductor can only be roughly estimated. Wind velocity is more important than ambient temperature in determining the rise in temperature of a conductor, while the effect of solar absorption decreases with rising conductor temperatures until at relatively high temperatures it becomes negligible.

Curve (*c*) in Fig. 6 shows the approximate current loading of

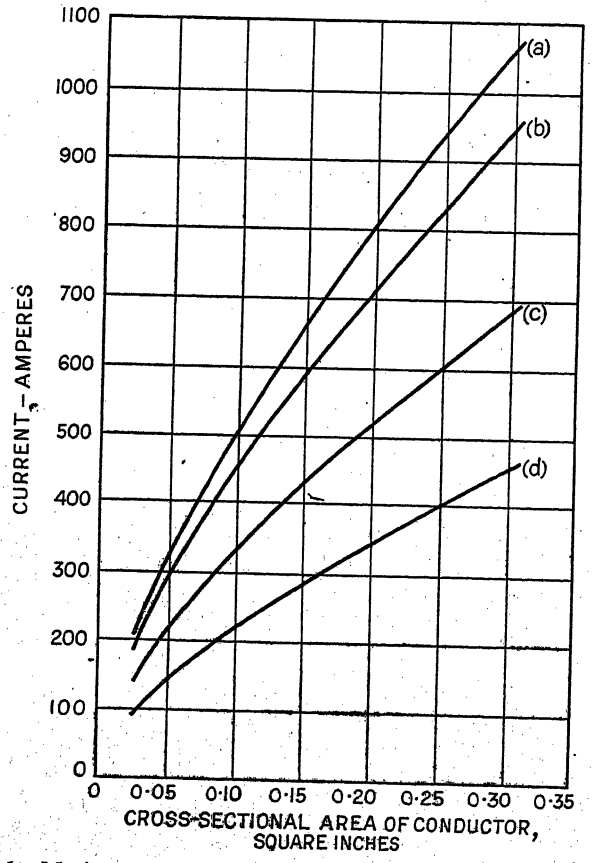


Fig. 6.—Maximum current loadings of hard-drawn stranded conductors erected out of doors.

(*a*) Cadmium-copper (equivalent copper cross-sectional area); max. working temperature 150° C (302° F).
(*b*) Cadmium-copper (actual cross-sectional area); max. working temperature 150° C.
(*c*) Copper; max. working temperature 80° C (176° F).
(*d*) Copper; max. working temperature 50° C (122° F).

stranded hard-drawn copper conductors for a maximum operating temperature of 80° C (176° F). The curve has been calculated for an assumed ambient temperature of 30° C (86° F) with a 1-m.p.h. wind, the conductor being assumed to be new and bright and solar absorption being ignored. This is obviously a very conservative basis for lines erected in this country, since the ambient temperature is seldom as high as 30° C and the wind velocity is usually over 1 m.p.h. Also, when the surface of the conductor becomes weathered and blackened the heat dissipation is increased, probably resulting in an increase of at least 10% in current loading. It would appear, therefore, that the loadings given by the curve are very safe and that under ordinary conditions of service, particularly with short-period intermittent loading, much higher currents could be carried without danger of the temper of the copper being seriously affected. For purposes of comparison curve (*d*), showing the relative current rating of copper conductors for a maximum operating temperature of 50° C (122° F) under otherwise similar conditions, is also included.

Considerably higher current loadings would be possible with conductors of copper containing about 0·1% of silver before there was any serious danger of loss of strength due to softening of the hard-drawn metal, but line losses at such current densities would be appreciable and would not in normal circumstances be economical, quite apart from the bad voltage regulation which might also result.

(3) HOLLOW COPPER CONDUCTORS

To avoid corona loss at voltages of the order of 110–132 kV it is necessary to use a conductor of only about ½in dia., corresponding to a cross-sectional area of rather less than 0·175 in^2, which is reasonable for most main lines, but at higher voltages, for instance 220 kV, the diameter necessary to avoid corona must not be less than about 1 in, which, with a normally stranded conductor, would correspond to an unnecessarily large cross-sectional area. For this reason alternative designs have been introduced whereby a large overall diameter can be obtained with a reasonable cross-sectional area of copper.

A number of designs of such "hollow conductors" are shown in Fig. 7. (A) is a cellular conductor consisting of a number of small copper tubes formed by drawing flat strip through a die; (B) is similar to (A) but the outer layer is composed of solid wires and the tubes may be of brass, bronze or other copper alloy; (C) consists of copper wires stranded round a spiral strip of copper or bronze forming a supporting core. In this country conductors of these types have been used mainly for substation connections and busbars, though they could be used as line conductors in suitable circumstances. Somewhat similar types such as (D) have in fact been used fairly extensively for line conductors in America.

The type illustrated as (E) employs a twisted I-beam as a core, the first layer of solid wires being stranded round it in the opposite direction to the twist in the core. (F) is a modification of (E) using six twisted I-beams, and other similar combinations have also been made up. (G) is somewhat similar to (C), solid copper wires being stranded round a spiralled bronze-core wire; the type has been used only to a very limited extent.

(H) is the Heddernheimer "H.H." conductor in which a number of spiralled sections are dovetailed into one another and so form a flexible tube with smooth inner and outer surfaces. (J) is a somewhat similar construction in which the strips are held together by elliptical key wires. In some cases the weight of the "H.H." conductor has been even further reduced by forming the interlocking sections with concave inner surfaces, the smooth external surface being unaffected. The "H.H." type has the lowest weight/diameter ratio of any of the "hollow conductors" so far used as line conductors, though the tensile strength per unit of cross-sectional area of copper is slightly

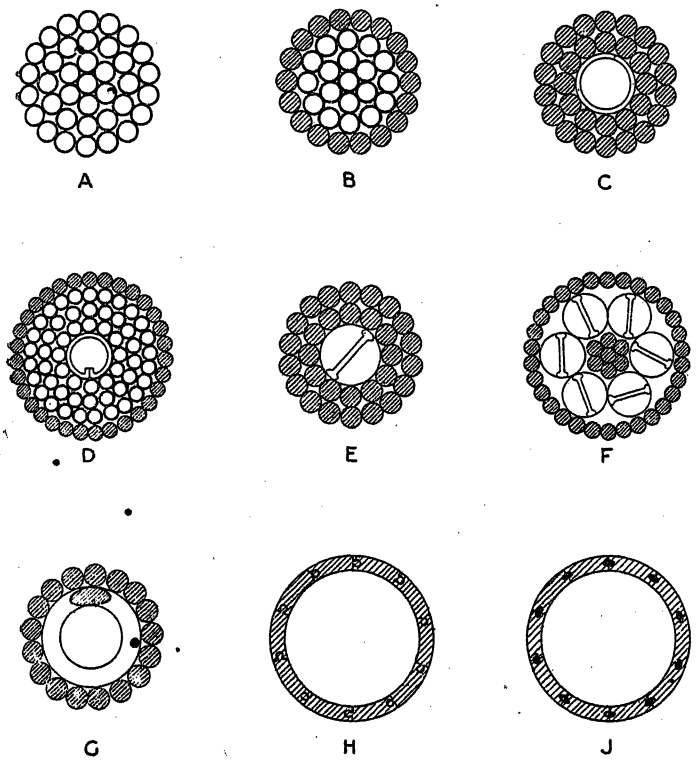


Fig. 7.—Typical hollow copper conductors.

lower than that of the other types. It will also be appreciated that as the conductor consists of a single layer the torque developed on stressing is not for the most part neutralized, as is the case with a conductor having alternate layers stranded in opposite directions. Thus the conductor has some tendency to twist, a factor which may have to be taken into account, especially during erection. With the first conductors erected a special torque arm was used on the end of the conductor to prevent twisting as it was run out, but this was subsequently found to be unnecessary.

"H.H." conductor is less flexible than the other types mentioned but is much more so than might be expected from an examination of a short length. When the conductor was first used it was run out under tension over sheaves 4–5 ft in diameter, whereas subsequently it was strung slack over sheaves half that size without difficulty.

If necessary any of the "hollow" conductors composed of stranded tubes or wires may be reinforced to give a greater tensile strength by the incorporation of high-tensile copper alloy or steel wires. Copper-alloy or copper-clad steel wires may be incorporated in the conductors in any convenient position, or a core of steel wires suitably protected from corrosion by one of the methods described in a later Section of the paper may be employed. For example, steel wires could take the place of the seven centre tubes in types (A) and (B), or the seven centre wires of type (F).

Hollow copper conductors have given good operational service and have not proved to be particularly susceptible to vibration, though their performance in this respect has been very closely watched. It has been claimed that the "H.H." type, owing to its greater stiffness, develops a smaller amplitude of vibration than the other types under any given conditions.

Not only is the initial corona voltage for hollow conductors considerably higher than that for solid stranded conductors of similar cross-sectional areas, but their a.c. resistance is lower, which results in a lower power loss. Their current-carrying capacities for a given temperature rise are also greater on account of the greater surface area available for cooling, and the better disposition of the copper with regard to skin effect when carrying alternating currents.

No special difficulty is experienced with clamps and fittings for hollow conductors. Suspension fittings are clamped round the conductor in the usual way, the conductor being capable of withstanding the clamping pressure without reinforcement. At tension joints and clamps it is customary to support the walls by the insertion of solid copper or alloy wires or rod to fill the interior of the hollow portions. Compressed or drawn sleeve joints are used extensively, and "cone" or "wedge" type fittings have also been employed satisfactorily.

(4) CADMIUM-COPPER CONDUCTORS

The use of cadmium-copper conductors has been steadily increasing in this country during recent years. They have a tensile strength which is approximately 50% greater than that of copper conductors, and are thus capable of being erected on longer spans with the same sag.

The cadmium-copper alloy used for overhead-line conductors usually contains about 0·8–1% of cadmium, and this gives a mimimum guaranteed conductivity for the hard-drawn alloy of about 83% of the I.E.C. standard for annealed copper. This slight disadvantage is offset by its increased tensile strength, hardness and fatigue resistance and the higher annealing temperature already referred to.

An increase in cross-sectional area to compensate for the lower conductivity of the alloy, together with its greater strength, results in the tensile strengths of standard cadmium-copper conductors being about 60% higher than those of equivalent sizes of copper conductor. Cadmium-copper has a resistance to atmospheric corrosion at least as good as that of copper, and in some conditions it has been claimed that it is even better.

Some details of a typical cadmium-copper conductor having an equivalent copper sectional area of 0·1 in^2 are shown in col. 2 of Table 1, and for purposes of comparison corresponding details of hard-drawn copper and steel-cored aluminium conductors are shown in cols. 1 and 3 respectively.

It will be noted that although the original weight of the cadmium-copper conductor is greater than that of the s.c.a. conductor, in the loaded condition with $\frac{3}{8}$in ice and 8 lb/ft^2 wind loads the resultant loads which determine the conditions of erection are practically equal. It will also be noted that while the maximum sags for the two conductors on equal span lengths are approximately the same under the assumed conditions of erection, the maximum wind load and deflection of the cadmium-copper conductor are appreciably less than those of the s.c.a.

The small diameter, which is of considerable advantage in reducing the wind and ice loading on the conductor, is of course a disadvantage when the conductor is for use with very high voltages (i.e. over, say, 132 kV), when the need for the prevention of corona may necessitate a specially large diameter. The majority of lines, however, operate at voltages at which the question of corona is unimportant, so that a conductor of small diameter may be used with advantage.

Owing to the greater unloaded weight of cadmium-copper conductors and the smaller wind loads to which they are subjected, their maximum horizontal deflection from the mid-position, due to wind pressure, is comparatively small, and the swing of insulator strings at the points of support is a minimum.

The relatively high modulus and low coefficient of expansion of cadmium-copper result in the conductor being subject to a

Table 1

	Hard-drawn copper	Cadmium-copper	Steel-cored aluminium
Equivalent copper section, in²	0·1	0·1	0·1
Stranding	7/0·136 in	7/0·146 in	7/0·173 in
Overall diameter, in	0·408	0·438	7/0·076 in 0·574
Ultimate tensile strength, lb	5 870	9 467	9 270
Assumed max. working tension:			
lb	2 935	4 500	4 500
percentage of ultimate strength	50	47·5	48·5
Weight per foot, lb	0·399	0·459	0·304
Wind load per foot with ice, lb	0·772	0·792	0·884
Resultant load per foot, lb	1·086	1·154	1·158
Virtual coefficient of expansion per deg F	$9{\cdot}22 \times 10^{-6}$	$9{\cdot}22 \times 10^{-6}$	$10{\cdot}5 \times 10^{-6}$
Virtual modulus of elasticity	18×10^{6}	18×10^{6}	$12{\cdot}8 \times 10^{6}$
Sags on 600-ft span:			
Maximum sag at 122° F without loads, ft	16·44	10·08	10·32
Minimum sag at 22° F without loads, ft	13·02	6·66	5·4
Variation in sag for 100 deg F variation in temperature, ft	3·42	3·42	4·92
Comparative maximum wind loading	0·97	1	1·12
Maximum horizontal displacement of conductor by wind at centre of 600-ft span, ft	9·26	5·4	8·1
Maximum angle of deflection of conductor by wind at 122° F	34°	33°	32°

minimum variation in sag with changes of load and temperature which helps to overcome "uplift" difficulties.

As can be seen from Fig. 3, the loss of strength of hard-drawn cadmium-copper is less than that of plain copper at comparable temperatures, and for a hard-drawn alloy wire containing, say, 0·8–1·0% of cadmium it may be assumed that for an equivalent loss in strength the working temperature is nearly 100 deg C above that for plain hard-drawn copper. To be conservative, a maximum permissible temperature of 150° C (302° F) has been assumed for the purpose of calculating the approximate current-loading curves (*a*) and (*b*) in Fig. 6, the conditions of ambient temperature, wind velocity and solar absorption being assumed to be the same as those for the copper conductors referred to in Section 2.3.

The erection of cadmium-copper conductors presents no particular difficulty. Like all conductors, they should be handled with reasonable care, although they do not require the exercise of any special precautions such as are necessary when handling conductors of softer materials. The usual types of tension and suspension fittings are suitable for cadmium-copper conductors, and owing to their relatively high hardness and fatigue strength, coupled with a freedom from the formation of high-resistance surface films, they present few jointing and clamping difficulties.

Approximate maximum sag curves at 122° F for a number of standard cadmium-copper conductors erected to a maximum loading of ⅜in ice with 8 lb/ft² wind with a maximum stress of 50% of the ultimate are shown in Figs. 8 and 9.

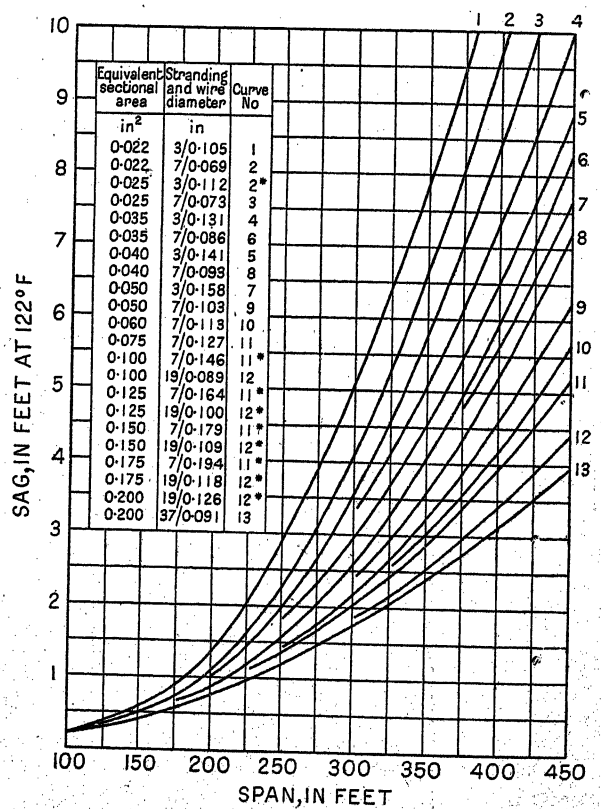


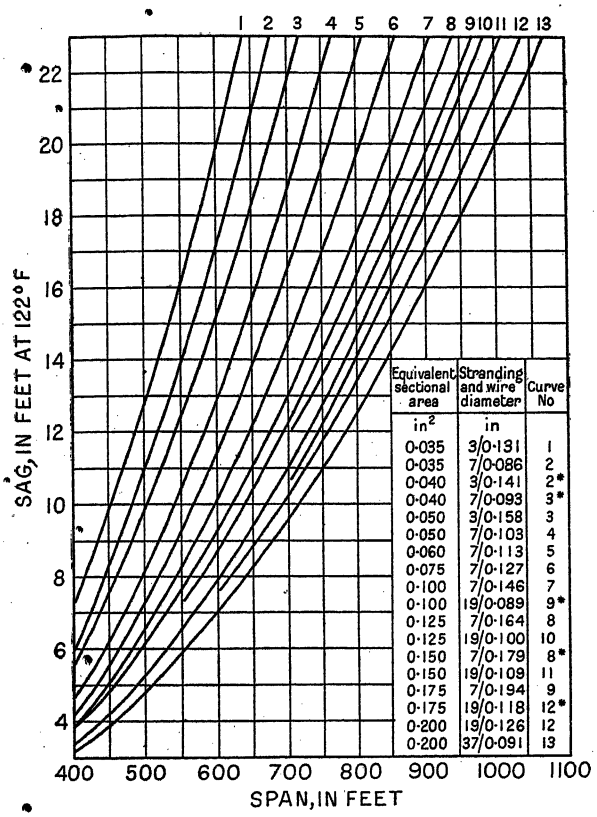
Fig. 8.—Sags at 122° F of standard cadmium-copper conductors, maximum stress 50% of the ultimate with ⅜ in ice and 8 lb/ft² wind at 22° F.

Asterisk denotes that curve is approximate only.

(5) REINFORCED COPPER CONDUCTORS

As an alternative to the use of a copper alloy, such as cadmium-copper, a high-tensile copper conductor can be produced by incorporating in it wires of a high-tensile material which may be either steel or a copper alloy such as bronze.

Such a reinforced conductor has the merit that the relationship between its electrical and mechanical characteristics can, within limits, be adjusted as required, such adjustment not being possible when the conductor is composed throughout of one material. If the reinforcing material is similar to copper in respect of modulus of elasticity, coefficient of thermal expansion, corrosion resistance and electro-chemical potential, such as is the case with bronze, no difficulty is encountered, but if the reinforcement has dissimilar characteristics difficulties may arise. This happens when steel reinforcement is used.



Equivalent sectional area	Stranding and wire diameter	Curve No
in²	in	
0·035	3/0·131	1
0·035	7/0·086	2
0·040	3/0·141	2*
0·040	7/0·093	3*
0·050	3/0·158	3
0·050	7/0·103	4
0·060	7/0·113	5
0·075	7/0·127	6
0·100	7/0·146	7
0·100	19/0·089	9*
0·125	7/0·164	8
0·125	19/0·100	10
0·150	7/0·179	8*
0·150	19/0·109	11
0·175	7/0·194	9
0·175	19/0·118	12*
0·200	19/0·126	12
0·200	37/0·091	13

Fig. 9.—Sags at 122° F of standard cadmium-copper conductors, maximum stress 50% of the ultimate with $\frac{3}{8}$ in ice and 8 lb/ft² wind at 22° F.

Asterisk denotes that curve is approximate only.

Dissimilar mechanical characteristics result in variable internal stress distribution, but in this respect there is less difference between copper and steel than between aluminium and steel, and in consequence there is considerably less variation in internal stress distribution in a steel-cored copper conductor than in a steel-cored aluminium conductor.

Mechanically, therefore, the association of copper and steel is a satisfactory one, but in regard to electro-chemical action and corrosion the position is not so satisfactory, and it has been the danger of accelerated corrosion of the steel reinforcing wires that has, until comparatively recently tended to retard the wide-spread use of steel-reinforced copper conductors. The problem has now been investigated and it has been found possible to produce steel-cored copper conductors which are practically immune from corrosion troubles.

About 10 years ago an investigation of various methods of protecting the steel core in a reinforced copper conductor was started, and test conductors have now been exposed for periods of nearly 10 years. At intervals samples have been removed for examination and tensile testing, and the investigation is still proceeding.

Test lengths of conductors with 21 different types of core protection were erected under light tension in a highly corrosive industrial atmosphere polluted by fumes from a rolling-mill and a residue-burning furnace in a position in which steam locomotives occasionally passed immediately underneath. Some of the conductors were also erected in a normal rural atmosphere for comparison. In all cases they consisted of a single layer of copper wires over the steel core, and most of them were composed of 12/·083 in copper wires and 7/·083 in steel wires.

The types of core protection investigated may be classified as follows:

(*a*) Metallic and non-metallic coatings applied to individual steel wires.

(*b*) Metallic and non-metallic coverings applied to the steel core as a whole.

(*c*) Waterproofing and rustproofing compounds applied to the conductor as a whole and/or to the steel core.

In addition to each of the above types of protection tried separately, various combinations were also investigated, as was the use of a stainless-steel core.

As a check on the conditions of the test, two lengths of steel-cored aluminium conductor composed of 12/·110 in aluminium and 7/·110 in galvanized-steel wires were exposed side by side with the other samples.

The results of some of the tests are given in Tables 2 and 3. Table 2 refers to conductors exposed in the severely corrosive atmosphere, and Table 3 to those in the rural atmosphere. None of the copper wires showed any appreciable signs of corrosion and their mechanical and electrical properties were not affected. Only the results of the tensile tests on the steel wires are therefore included in the Tables. The results of the tests on all the conductors are not recorded as some of the tests were discontinued after a period, either because they did not promise to yield any useful results or because it was not possible to continue them.

In considering the results of the tests, it is necessary to bear in mind that in those carried out in the industrial atmosphere an endeavour was made to select a site to represent as nearly as possible the worst conditions likely to be experienced in any locality. The conditions were therefore much more onerous than would normally be found in practice, and their severity may be judged by the results obtained with the steel-cored aluminium conductor. After about 9½ years' exposure the aluminium wires of this conductor had lost on an average 33–34% of their original tensile strength. The zinc coating on the outer wires of the steel core was badly corroded but the steel itself showed no signs of rusting and there was no reduction in its tensile strength.

The results obtained in the tests carried out in the rural atmosphere show that considerably less deterioration is to be expected under normal conditions of service than that found under the worst conditions. Nevertheless, to judge the probable behaviour of conductors, even under the severest conditions, conclusions should be based on the results of the industrial atmosphere tests and are as follows:—

(*a*) Galvanizing of the steel wires alone is not a satisfactory protection.

(*b*) The application of a bituminous compound to a galvanized core, while having some beneficial effect, does not provide adequate protection.

(*c*) There are types of compound or paint which promise to be much more effective than the bituminous or asphaltic compounds hitherto used, as is shown by a comparison of conductors (2), (5) and (6) in Table 2.

(*d*) Enamel or similar non-metallic coatings on steel wire promise to give good results and to be much more effective than metallic coatings. Such protection would be particularly suitable for single-wire cores because its extreme thinness would not affect the stranding. The coating used on the core of conductor (8) was purely experimental, was not of high quality and could be improved in commercial production. Even so it gave good results.

(*e*) For multiple-wire cores the best protection is some form of waterproof wrapping applied to the core as a whole.

(*f*) A stainless-steel core, though expensive, gives excellent

Table 2—Conductors Exposed in Highly Corrosive Industrial Atmosphere

No.	Stranding		Type of protection on steel core	Period of exposure		Average loss of strength of core wires		Remarks
	Copper	Steel		Years	Months	Outer wires	Centre wire	
						%	%	
1	12/·083	7/·083	Hot dip galvanizing on each wire	9	8	77	44	All steel wires very severely corroded
2	12/·083	7/·083	Ditto, but core treated with 65 penetration bituminous compound	9	8	29	Nil	Outer steel wires of core severely corroded; zinc coating on centre wire badly attacked
3	12/·083	7/·083	Galvanized wires—copper wires zinc-coated	7	10	54	13	Steel wires very severely corroded
4	12/·083	7/·083	Steel wires coated with copper by immersion in copper sulphate	5	3	45	Nil	Outer steel wires severely corroded; corrosion of centre wire starting
5	12/·062	7/·062	Galvanized wires—cores treated with 85/40 asphaltic compound	3	10	Nil	Nil	Zinc coating on outer wires severely corroded—rusting commenced
6	12/·083	7/·083	Galvanized wires—core treated with proprietary rust-proofing paint	7	3	Nil	Nil	Zinc coating on outer wires corroded at intermittent points, but no rusting
7	9/·118	7/·062	Galvanized wires—core covered with thin extruded lead sheath	8	5	Nil	Nil	Lead sheath severely corroded but steel wires unaffected
8	6/·128	1/·128	Plain steel wire, stove-enamelled	8	8	Nil	Nil	Enamel coating broken at intermittent points with slight corrosion of steel
9	12/·083	7/·083	Plain steel wires—core treated with 65 penetration bituminous compound and butt-lapped with cotton tape impregnated with bituminous compound	9	5	Nil	Nil	Minute signs of corrosion at pinholes in tape
10	12/·083	7/·083	Plain steel wires—core treated with red lead, lapped with impregnated paper and coated with 65 penetration bituminous compound	9	5	Nil	Nil	No signs of deterioration
11	15/·068	7/·085	Galvanized wires—core rubber covered	8	5	Nil	Nil	No signs of deterioration
12	12/·083	7/·083	Galvanized wires—core treated with 65 penetration bituminous compound and lapped with two reverse layers of cotton yarn impregnated in coal tar	8	3	Nil	Nil	No signs of deterioration
13	12/·083	7/·083	Galvanized wires—core lapped with 0·02in rubber tape	8	3	Nil	Nil	No signs of deterioration
14	12/·083	7/·083	Galvanized wires—core covered with extruded sheath of insulating material	7	10	Nil	Nil	No signs of deterioration
15	12/·062	7/·062	Galvanized wires—core coated with 65 penetration bituminous compound, and complete conductor treated overall with 85/40 asphaltic compound	3	10	Nil	Nil	No signs of deterioration
16	12/·083	7/·083	Stainless-steel wires	7	6	Nil	Nil	No signs of deterioration
	Aluminium	Steel				Aluminium wires	Steel wires	
S.C.A.	12/·110	7/·110	Galvanized wires	9	8	33	Nil	Aluminium wires severely corroded. Zinc coating on outer wires of core badly corroded. Coating on centre wire slightly corroded
	12/·110	7/·110	Galvanized wires—core treated with 65 penetration bituminous compound	9	8	34	Nil	Aluminium wires severely corroded. Zinc coating on outer core wires moderately corroded

Table 3

CONDUCTORS EXPOSED IN RURAL ATMOSPHERE

Conductor No.	Period of exposure		Average loss of strength of core wires		Remarks
	Years	Months	Outer wires	Centre wire	
			%	%	
1	9	6	12·5	Nil	Outer steel wires badly corroded—centre wire shows signs of corrosion without loss of strength
2	9	6	11	Nil	Outer steel wires corroded, centre wire not affected
9	9	6	Nil	Nil	Minute signs of rusting at pin-holes in tape
10	9	2	Nil	Nil	No signs of deterioration

results, the tests confirming that even under bad atmospheric conditions there is no apparent electro-chemical reaction between such steel and copper.

In addition to the types of core protection investigated in the above tests, several others have been tried at various times, including wrapping the steel core with a bimetallic or even a single metal tape, with what success the authors do not know.

Another widely used type of reinforcement for copper conductors is a core of copper-clad steel wires. Conductors reinforced with such wires have proved to be entirely satisfactory in service, and they are referred to in greater detail in a later Section of the paper.

(5.1) Wrapped-Core Conductor

As can be seen from the above, the best test results were in general obtained with conductors having some form of covering applied to the core as a whole. Of the coverings tried, those consisting of a wrapping of impregnated paper, cotton tape or yarn would appear to be the most promising, at least for application to cores of larger diameter. Of these three materials the cotton tape may be the best from the point of view of effectiveness combined with ease of application and low cost. Although in the test conductor with this type of protection some minute signs of rusting of the ungalvanized steel wires are discernible after 9½ years' exposure, it should be borne in mind that this conductor was the first made and was purely experimental; a rather coarsely woven tape was used and it was applied without any overlap to a core of plain steel wires.

Subsequent experience with this type of core wrapping indicates that a fairly closely woven tape is to be preferred, and that while its actual thickness is not critical one about 8–10 mils thick is satisfactory, provided it is properly impregnated with a suitable waterproof compound and is applied with reasonable care, preferably with a slight overlap. A liberal application of compound to fill the interstices between the core wires may also be helpful, as may be a similar application to the taped core before the copper wires are laid round it. The compound should be so blended that it remains soft at all normal temperatures and yet is not sufficiently fluid to drain out at high temperatures. There is no difficulty in providing such a compound, particularly when the tape is there to help hold it in position.

The tests referred to above indicate that in normal circumstances, if the core is taped correctly, galvanizing of the core wires may not be necessary. The elimination of the galvanizing gives rise in the case of a multi-wire core to a saving in cost which largely offsets the cost of applying the tape. Galvanized wires may, however, be used as a double safeguard.

Conductor with a wrapped core does not present any special difficulty in handling or erection, and the usual types of suspension fittings and tension clamps are suitable. No difficulty is experienced in holding the full breaking load of the conductor in snail clamps. The usual type of cone joint similar to that used on s.c.a. conductors but made of copper alloy can be used for joints under tension, and reference is made in a later Section of the paper to an improved form of compressed sleeve joint which has special advantages.

Some doubts as to the possible life of the taping have been expressed—particularly its ability to resist damage under service conditions when subjected to vibration. Only prolonged experience in service can prove or disprove the authors' belief that the effectiveness of the protection will not be seriously impaired under normal conditions. If suitable grades of tape and compound are used no appreciable deterioration in quality should occur. The core covering is protected by the outer copper wires from external mechanical damage and the direct effect of atmospheric conditions. In the conductor which has been under test, after 9½ years the tape and compound appear to all intents and purposes to be almost exactly as they were when the conductor was made.

So far as damage due to vibration and movement in service is concerned, there would appear to be no reason why any deterioration at tension clamps should occur, since relative movements of the conductor wires would in all normal cases be almost non-existent. At suspension fittings where a greater degree of bending is to be expected it also seems doubtful whether with properly designed fittings the effectiveness of the tape covering would be impaired, even after long periods in service. In this connection it should be borne in mind that the amplitudes of vibration likely to occur with steel-cored copper conductors should be very much less under normal conditions of service than those which occur with steel-cored aluminium conductors, for the reason that their average density is greater.

(5.2) Three-Wire Reinforced Conductors

All the tests mentioned above and the conclusions drawn from them apply only to steel-reinforced copper conductors in which the arrangement is such that the copper wires completely surround the steel wire or wires of the core. The protection of steel wires for use as reinforcement in 3-wire conductors, in which either one or two of the wires are of copper, requires special consideration, since not all of the protections mentioned above would give adequate service if directly exposed to the atmosphere. Three-wire conductors have advantages, particularly in the smaller sizes, which make them specially suitable for use in rural areas. They are, for instance, cheaper to make, are robust and relatively free from vibration. Whenever possible, copper alloy wires should be used for their reinforcement, or the whole conductor should be of an alloy such as cadmium-copper. It is then composed throughout of corrosion-resisting material, and is likely to give satisfactory service under nearly all conditions. If, however, steel reinforcing wires are used in a 3-wire conductor the protection applied to them must be capable of withstanding not only normal atmospheric attack but also mechanical damage, such as may be caused during erection or by flashovers, lightning or abrasion in service.

Conductors composed of one or two copper wires with a reinforcement of ordinary galvanized wires have sometimes been put into service. It would appear, however, that such con-

ductors are, under most conditions, likely to give insufficiently reliable service. Again, both copper and steel wires have been galvanized before stranding, and it is possible that they may give reasonable service for a time in suitable localities if a satisfactory zinc coating on the wires can be obtained. Steel wires protected with the usual type of braided weatherproof covering in addition to galvanizing have also been employed, but the life of such coverings is usually limited.

Other types of protection for steel reinforcing wires in 3-wire conductors have included various types of electro-deposited metallic coatings, e.g. copper, applied either directly to the steel wire or over a zinc coating. Provided such coatings are sufficiently thick and non-porous, satisfactory results may be obtainable, but they cannot in general be recommended.

The most widely used type of steel reinforcement for 3-wire copper conductors has been copper-clad steel wire, and copper conductors incorporating such wire have been used very extensively in rural areas in America and have proved entirely satisfactory.

(5.3) Ultimate Tensile Strength

The ultimate tensile strength of a steel-reinforced copper conductor can be adjusted over a wide range by varying the number and tensile strength of the component wires. It cannot, however, be calculated with any high degree of accuracy, but after a large number of tests on different types of steel-reinforced copper conductors it was found that their ultimate strength could be determined with sufficient accuracy for practical purposes by taking 85% of the sum of the breaking loads of the steel wires plus 98% of the sum of the breaking loads of the copper wires as determined on the wires before stranding.

(5.4) Modulus of Elasticity and Coefficient of Expansion

If the effect of stranding is ignored in calculating the virtual modulus of elasticity and coefficient of expansion, the following formulae apply to steel-reinforced copper conductors:—

$$E_v = \frac{18m + 28}{m + 1} \times 10^6 \text{ lb/in}^2$$

$$\alpha_v = \frac{9{\cdot}22m + 9{\cdot}95}{m + 1{\cdot}55} \times 10^{-6} \text{ per deg F}$$

where E_v = virtual modulus of elasticity of the composite conductor

α_v = virtual coefficient of expansion of the composite conductor

m = ratio of total cross-sectional area of copper to that of steel

and where it is assumed that

E for steel = 28×10^6 lb/in^2
E for copper = 18×10^6 lb/in^2
α for steel = $6{\cdot}4 \times 10^{-6}$ per deg F
α for copper = $9{\cdot}22 \times 10^{-6}$ per deg F

The curves in Fig. 10 give the approximate virtual modulus and coefficient for any value of m.

(6) COPPER-CLAD STEEL CONDUCTORS

From time to time attempts have been made by different processes to produce copper-clad steel wire, but the only really satisfactory material which has been manufactured and used to any large extent up to the present is that known as Copperweld.

In the production of this material, copper is cast round a heated billet of steel under controlled conditions in such a manner that the copper and steel are welded together. The billet is subsequently rolled and drawn to produce a wire having a steel core encased in a sheath of copper to which it is welded throughout its length.

It is somewhat remarkable that a composite material consisting of metals as different in physical properties as high-tensile steel and soft copper should be capable of being rolled and drawn, maintaining at all stages approximately the same cross-sectional proportions of steel to copper. It is claimed that the ability of the material to withstand such processes is the best possible guarantee of a uniformly good bond between the copper and steel.

In the course of manufacture care has to be taken to ensure

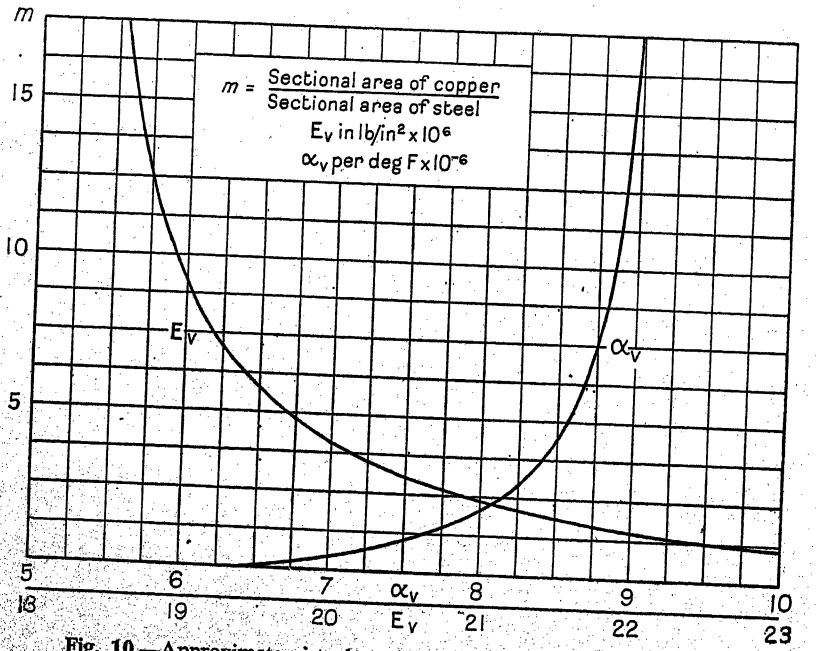


Fig. 10.—Approximate virtual modulus and coefficient of expansion of steel-cored copper conductors.

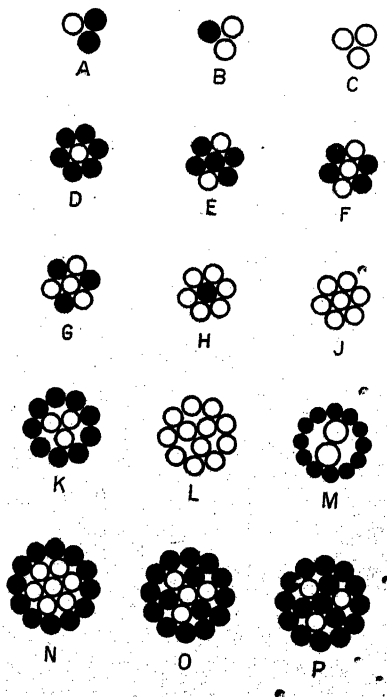


Fig. 11.—Steel-reinforced copper conductors. Typical combinations of copper and copper-clad steel wires. Solid circles are copper wires.

that there is no undue eccentricity of the steel core in the finished wire, and that an adequate thickness of copper exists at all points of the circumference. An excessive thinning of the copper sheath at any point, such as may result if the shape of the steel core is deformed appreciably from the requisite circularity in section, might give rise to danger of perforation of the copper and subsequent failure due to corrosion. Such a possibility is, however, guarded against in the course of production, and the makers guarantee a minimum thickness of copper at any point, the actual thickness of the copper sheath being accurately measured by an ingenious magnetic method. So long as the copper sheath remains intact, such wire has a corrosion resistance as good as that of a solid copper wire, combined with an appreciably higher tensile strength.

Two standard types of wire are produced having different proportions of copper to steel. One type has a conductivity 40% of that of a solid copper wire of equal overall diameter, and the other a conductivity of 30%. Ultimate tensile strength varies from about 50 to 170% higher than that of hard-drawn copper, according to type and size and the quality of the steel.

The average modulus of elasticity of the wire is stated by the makers to be approximately 24×10^6 lb/in^2, and the coefficient of linear expansion about $7{\cdot}2 \times 10^{-6}$ per deg F.

These copper-clad wires may be used alone or in any desired combination with hard-drawn copper wire to produce a wide range of conductors having characteristics to meet almost any requirement in which enhanced mechanical strength is required. Some typical arrangements of stranded copper conductors incorporating copper-clad steel-wire reinforcement or composed throughout of such wire are shown in Fig. 11.

Three-wire conductors composed of one Copperweld and two copper wires have been used very extensively and successfully in America for rural electrification lines, the most popular sizes being those of approximately 0·02 in^2 and 0·013 in^2 equivalent copper sections, having nominal breaking loads of about 2 580 lb and 2 230 lb, respectively.

(7) CONDUCTOR JOINTS

It is not intended here to review current practice in making tension and other joints in overhead-line conductors, but to refer to some recent developments with one particular type of joint.

It is no secret that mechanical joints such as are usually described as "cone" joints have not in all cases proved satisfactory; in fact for a number of years their use has been declining in favour of other types, though they are more satisfactory on copper or copper-alloy conductors than on aluminium conductors.

Twisted or notched sleeve joints have been used extensively and quite satisfactorily on copper conductors for many years, but they have mainly been applied to the smaller sizes. Joints of the compressed, drawn or rolled sleeve types have been gaining in popularity for all sizes of conductor for a number of years and are now beginning to come into wider use in this country. It is to the compressed sleeve type of joint that special reference is made below.

There is nothing new about the idea of compressing a sleeve or socket on to a conductor for jointing purposes, and compressed joints were certainly in service on overhead-line conductors in Canada and possibly elsewhere over 40 years ago. They have been applied extensively to aluminium and steel-reinforced aluminium conductors and have now been adapted for use with copper, cadmium-copper and steel-reinforced copper conductors.

(7.1) Compressed Sleeve Joints for Cadmium-Copper Conductors

In making a joint of this type the sleeve is compressed on to the ends of the conductor between the dies of a hydraulic press. Although a hand-operated press of compact form can be used, it is nevertheless a fairly heavy machine, weighing in the case of the larger sizes of conductor about 2–4 cwt, and is one which, in normal circumstances, can be used only on the ground. This disadvantage appears, however, to be unavoidable and must be balanced against the advantages of the compressed joint, which experience has shown to be considerable.

After numerous tests a sleeve of the shape and dimensions shown in Fig. 12(*a*) and weighing about 4½ lb was found to be satisfactory for a 19/·118 in cadmium-copper conductor having a minimum specified breaking load of 17 083 lb. The sleeves were cast in cadmium-copper, and in this form they are considerably cheaper than other types of tension joint hitherto employed. It was found that they could be used in the "as-cast" condition, there being no need for any special cleaning or finishing. The "as-cast" interior surface of the sleeve had no detectable influence on the electrical efficiency of the joint, and on test the joints could be guaranteed to develop at least 95% of the nominal tensile strength of the conductor.

Tests showed that there was no advantage in using a sleeve longer than 12 in, and sleeves 16, 21 and 23 in long gave no higher tensile strengths than that obtained with the 12in sleeve. In all cases the finished diameter of the joint after compression was 1¼ in, and the final length of the 12in sleeve was about 14 in. In eight consecutive tests on 12in sleeve joints 97·3–104·7% of the nominal tensile breaking load of the conductor was obtained, and the average was over 100%.

The length of the die used to compress the sleeve was 2 in, and the maximum total pressure applied was about 60 tons. In making the joint each compression should overlap the previous one by about 50%. A die longer than 2 in could, with advantage, be used, and one about 3 in long should normally be suitable, if the press is powerful enough.

The method of compressing the sleeve, whether in steps from the centre outwards, from the ends to the centre or from one end to the other, had no apparent effect on the efficiency of the joint. A convenient procedure is to locate the sleeve, give it one compression in the centre to hold the conductor ends in position, and then, by a series of operations, to compress the sleeve in steps from the centre towards the ends.

A sleeve of the overall dimensions shown in Fig. 12(*a*), although particularly designed for a 19/·118 in cadmium-copper conductor having a diameter of 0·59 in, could be used satisfactorily for a range of conductors if the bore were suitably adjusted. It is known to be effective on a conductor with a diameter as small as ¼ in, but would normally be much too heavy and cumbersome for such a light conductor. The advantage of maintaining the outside cross-sectional dimensions of the sleeve constant over as large a range of sizes as possible is, of course, that the same set of compressor dies can be used over the whole range.

To help in locating the joint a central stop can be incorporated in the sleeve. This may take any convenient form, such as a small protrusion cast on to the inner wall of the sleeve or a pin inserted through the wall. A stop which does not appreciably obstruct the clear line of vision through the sleeve is to be preferred so that the interior can readily be examined to ensure that it is clean and free from obstructions.

(7.2) Compressed Sleeve Joints for Steel-Cored Copper Conductors

The jointing of a steel-cored conductor is not as simple as that of a conductor which is composed of the same material throughout. The use of separate sleeves for the steel core and the conducting wires necessitates the use of two sets of dies and the carrying-out of two series of compressing operations. It usually gives rise also to slight "birdcaging" of the outer wires

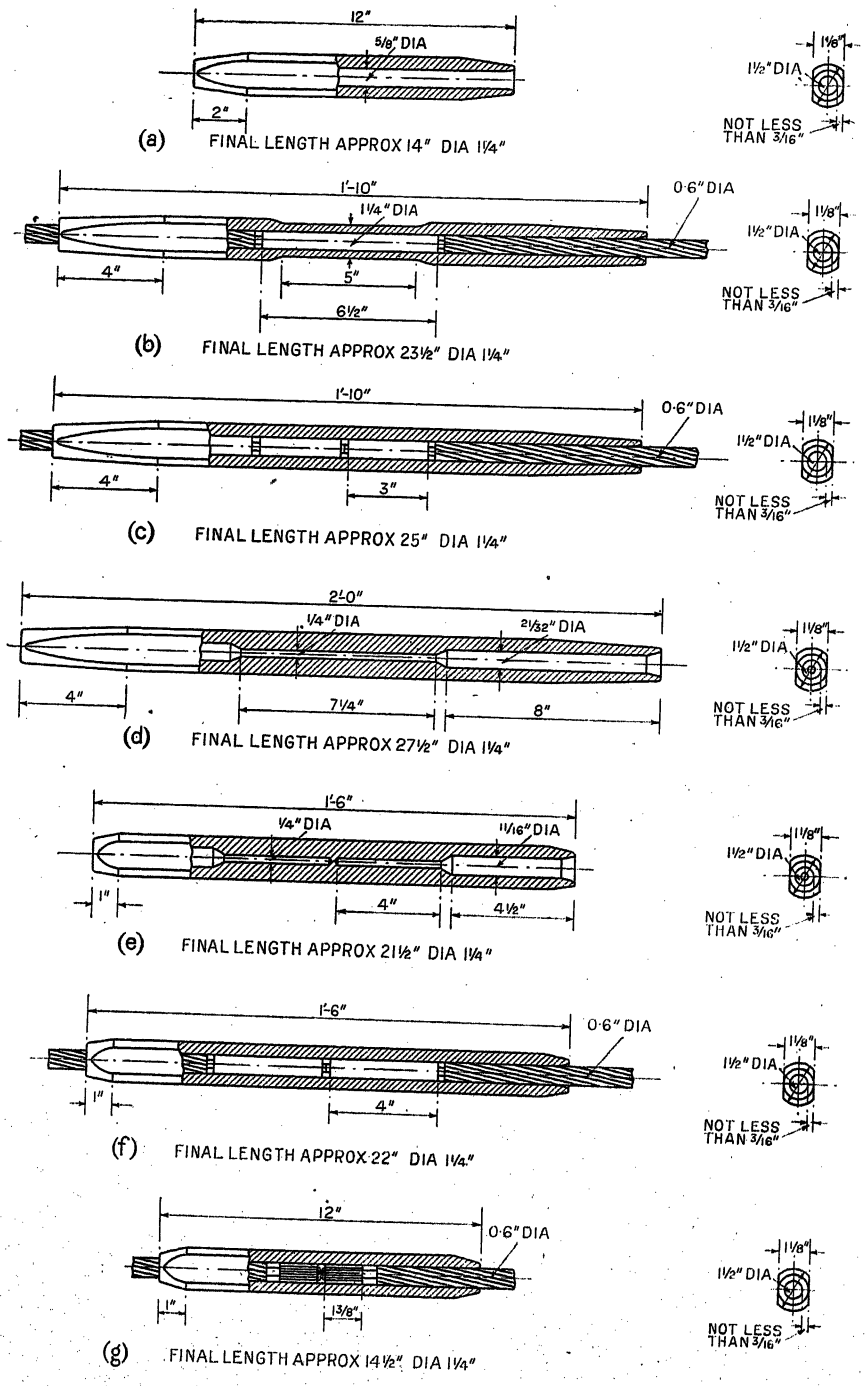


Fig. 12.—Compressed sleeve joints for cadmium-copper and steel-cored conductors.

near at least one end of the sleeve. In practice this is seldom of great consequence and the "caging" is usually soon lost in the length of the conductor, but at times has to be dressed back to reduce it, particularly in a conductor having the core treated with compound, which appears to have the effect of preventing the outer wires from sliding freely over the steel. In any event, "caging" is best avoided if possible, and in general this can be achieved only by compressing the sleeve from the ends towards the centre with the steel core free to move relatively to the outer wires as the sleeve elongates, which is not possible if the ends of the core are jointed together before the outer sleeve is compressed.

All the joints shown in Figs. 12(*b*) to (*g*) were designed for a 0·175 in² copper equivalent conductor composed of 30/·087 in copper and 7/·075 in steel wires with a wrapping of impregnated tape on the core. The outside diameter of this conductor is 0·609 in, and the outside cross-sectional dimensions of the copper sleeves used were the same as those of the sleeve for a cadmium-copper conductor having the same equivalent cross-sectional area, so that the same set of compressor dies could be used for both joints.

On test a joint as shown in Fig. 12(*b*) gave satisfactory results, developing over 96% of the nominal breaking load of the conductor (16 740 lb). In this the steel core was separately jointed with a steel sleeve as in s.c.a. joints.

A joint as shown in Fig. 12(*c*) had two separate steel ferrules compressed on to the ends of the steel cores, and a copper sleeve compressed over the whole conductor in steps from the ends towards the centre, thus overcoming any tendency to "cage" the outer wires. It developed about 98% of the conductor strength.

The design shown in Fig. 12(*d*) eliminates the ferrules and consists of a single copper sleeve having differential bores. In six consecutive tests the results obtained were between 95·0 and 97·1% of the nominal tensile strength of the conductor. A test on the sleeve itself showed that it had a breaking load of 28 500 lb, or about 70% greater than that of the conductor.

Before the ends of the conductor were inserted into the sleeve the tape was removed from the exposed portions of the steel core. If this was not done it was found that the core had a tendency to slip in the sleeve after compression.

A cast sleeve joint of the dimensions shown in Fig. 12(*e*) was found to have a tensile strength of over 95%.

The joint shown in Fig. 12(*f*), which employs a sleeve of uniform bore with separate copper ferrules on the steel cores, behaves in a manner similar to that of a single-piece sleeve having differential bores, and costs less.

The modified form of copper ferrule shown in Fig. 12(*g*) increases the effective length of grip on the steel core and enables the length of the joint sleeve to be reduced. After the ferrules have been slipped over the cores the steel wires are opened out, bent back and located in the seven longitudinal grooves. The ends of the conductor with ferrules in position are then inserted into the sleeve, which is compressed in steps from the ends towards the centre.

With a 12-in sleeve over 95% of the nominal strength of the conductors can be developed, and it seems probable that a sleeve only 10 in long before compression would be sufficient.

It may be helpful to apply a coating of suitable grease or compound to the ends of the conductor before they are inserted into the sleeve. If there is any fear that moisture may gain access to the centre of the joint by capillary action through minute interstices left between the copper wires after compression, a washer of some material such as rubber can be located between the ferrule and the ends of the copper wires so that after compression it forms a positive seal.

(7.3) Dimensional Changes of a Sleeve during Compression

The initial compression of a joint is accompanied by an elongation of the sleeve which, until the latter is pressed into intimate contact with the conductor, can be taken up by relative movement between the sleeve and the conductor. As soon as the sleeve has been pressed on to the conductor, however, it is no longer free to elongate independently, and both sleeve and conductor wires proceed to elongate together. When the conductor is composed of wires of dissimilar materials such as steel and copper, the copper wires elongate when compressed but the steel wires do not, because the pressure applied to them through the copper is insufficient to cause them to do so. There is therefore relative movement of the steel and copper wires.

When a sleeve is compressed in steps from the centre towards the ends, part of its extension results in an elongation of the copper wires which causes them to be pushed back relatively to the core if the latter is not free to move with them. Unless the slackness of the wires so produced can be dissipated by their movement relative to the core over an appreciable length of conductor, which movement a compounded tape covering on the core tends to restrict, "birdcaging" of the copper wires will occur in the conductor immediately outside the end of the sleeve.

If the sleeve is compressed from the ends towards the centre, some portion of its elongation results in the ends of the conductor separating and a gap being left between them at the centre of the joint when completed; the remainder causes an elongation of the copper wires relative to the steel core which results in the length of core beyond the end of the copper wires being reduced. Both of these changes must be allowed for in making a joint if "caging" of the outer wires is to be avoided.

For example, in the joint shown in Fig. 12(*g*) very roughly half the total extension of the sleeve (about 2 in) is taken up by its elongation relative to the conductor and half by its elongation with the outer wires of the conductor. To ensure that the minimum length of gap is left between the ends of the conductor when the joint is finished, it is therefore necessary to insert the end of the conductor with its ferrule which is to be compressed first, so that it is located about $\frac{1}{4}$ in beyond the centre of the sleeve. After compression the end should then be about $\frac{1}{4}$ in short of the original centre, and if the second conductor end is then inserted so that it butts up to the first end there should be a gap of about $\frac{1}{2}$ in between the ends after the sleeve has been fully compressed.

To take up the relative movement of the copper and steel wires, since the core cannot withdraw from the ferrules, it is necessary to leave between the ends of the copper wires and each ferrule a gap of about $\frac{1}{2}$ in. After compression this gap should be closed. If such a gap is not provided, the ends of the copper wires exert a pressure on the ferrule which results in the steel core being pulled back relative to the copper wires, causing "caging" of the latter just outside the end of the sleeve in exactly the same manner as occurs when the sleeve is compressed from the centre outwards towards the ends. This action, however, might not be as pronounced in the case of a conductor in which a more efficient grip on the steel core could be obtained by pressure through the copper wires than is possible when the core is covered with impregnated tape.

(8) ACKNOWLEDGMENTS

The authors wish to express their indebtedness to the Copperweld Steel Co. and the Copper Wire Engineering Association (U.S.A.) for the diagrams reproduced in Figs. 1 and 2 respectively; to Thos. Bolton and Sons, Ltd., for the information upon which Fig. 3 was based; and especially to British Insulated Cables, Ltd., for their co-operation and great assistance in carrying out the corrosion tests on steel-cored copper conductors.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 12TH APRIL, 1944

Dr. J. L. Miller: The paper deals most adequately with all significant aspects of copper conductors, striking, I consider, the most pertinent balance between the chemical, metallurgical and engineering aspects of the problem. I think, however, that it would have been an improvement if a bibliography had been included; in particular, no reference is made to the large amount of previous work on hollow conductors both in Europe and in the U.S.A. Also, in the introduction, aluminium conductors should have received more notice. These conductors are widely used and the lack of reference to them there, where every type of copper conductor is catalogued, together with those isolated and brief references made throughout the body of the paper, can only create in the reader's mind the impression that the treatment is not without bias. This would be an unfair criticism, but the authors could have avoided any risk of it by referring to aluminium in the introduction.

I find Section 2.2, particularly the remarks on the effects of impurities on the softening temperature of copper, most in-

structive. Why, however, have tellurium and selenium, which have a pronounced effect on the properties of copper, been omitted from the discussion, particularly as these elements may exist in copper in amounts equal to those of silver?

While I do not question that a limit must be fixed for the maximum operating temperature, I would ask whether in most practical cases anything near the 80° C set down by the authors is likely to be attained, as there is not much doubt that voltage drop will be the governing factor. In any case, 80° C is cited as the maximum for long periods, which is an ambiguous qualification. I do not see any way round the difficulty, except to ensure that the maximum temperature ultimately chosen is sufficiently conservative.

In Section 4, I agree with the authors that cadmium-copper conductors are very satisfactory and have numerous advantages; for instance, their relatively smaller diameters as compared with s.c.a. conductors reduce wind and ice loading. Nevertheless, there is a tendency to take excessive advantage of the excellent mechanical properties of these conductors, with the result that other troubles may ensue unless suitable precautions are taken.

Section 5 is extremely important. It appears from Table 2 that many of the core protections studied by the authors, i.e. those in conductors 10–16, are very satisfactory. Being familiar with the test site, I have no doubt that the corrosive conditions present were very severe. It is also interesting to realize from the conditions of conductors 1, 2 and 9 (already shown to be unsatisfactory in the industrial atmosphere) after the tests referred to in Table 3, that even a rural area can give rise to corrosion trouble. This, of course, is only to be expected, but it serves to drive home the fact that under every condition of installation, full protection of the core must be ensured.

While on the subject of corrosion, however, I think it necessary to emphasize the fact that the tests described were practical corrosion trials and not laboratory accelerated tests. It is a pity, though, that some suitable artificial accelerated test has not yet been devised. My experience, and that of my colleagues, is that one test specimen, thought to be better than another as a result of laboratory tests, is often found in practice to be actually worse. I should like to hear the views of the authors on this point.

In Section 3, most of the previously employed types are shown in Fig. 7. While all of them have their merits, I think that the most attractive ones, taking all factors into consideration, are the hollow segmental and twisted I-beam conductors, i.e. those shown in Fig. 7, E, H and J. The advantages of the segmental conductor are many. It has the lowest cross-sectional-area/diameter ratio of any of these large-diameter conductors, an adequate tensile strength per unit area, a very smooth surface, and adequate flexibility. In addition, the a.c. resistance is almost equal to the d.c. resistance, and compared with the stranded conductor even a violent flashover does relatively less harm. During erection, too, the fact that there may be a tendency to twist because the torque developed on stressing is not neutralized does not appear, so far as our limited experience goes, to give rise to any actual difficulty. It has also been stated that this conductor is not susceptible to vibration trouble, no doubt owing to relative movement between segments introducing a self-damping effect.

My colleagues, Mr. Clements and Mr. Fuller, and I have been able to produce experimentally and erect under full-scale laboratory conditions short lengths of this conductor, and from the knowledge we have so far obtained it appears that all the claims made by previous users are substantiated. As regards production, it can be produced on plant not too far removed from standard, but to make it a good manufacturing proposition special plant is undoubtedly necessary.

We have also made several versions of the twisted single I-beam conductor and there appears to be little difficulty in producing a satisfactory article on standard plant.

The remaining conductors all appear to have one or more shortcomings in regard to manufacture, production or jointing, and many of them in addition have the disadvantage of large weight/diameter ratios. Conductors G and F can be particularly criticized for overhead-line work, F most specifically on account of manufacturing complication; in this case, the six I-beams would have to be twisted separately unless special plant was employed.

Mr. J. R. Harding: In Section 2.1 the authors deal with conductor elongation. It seems to me that, having determined the permanent extension, a simpler method of allowing for this is to erect the conductor to a sag corresponding to a lower temperature such that the reduction of length due to temperature is equal to the increase of length due to permanent extension. It is then automatically compensated without any special calculations, because the permanent stretch and expansion are both functions of length.

Type (C) in Section 3 has been used mostly for substations, but is the same type of conductor, and is made on the same plant, as hollow conductor for oil-filled cables. Has this conductor been tested for line purposes? The central spiral is, after all, performing the same function as the I-beam in Type (E) and, if it is sufficiently rigid to maintain the circular form, it should be quite adequate. Were the tests on steel-cored copper carried out on conductors actually carrying current and with superimposed variations of temperature? I agree with Dr. Miller that nothing takes the place of a long period in actual service.

With steel-cored conductors it is very necessary for cone tension clamps and joints to be such that the lay of the strand is not disturbed, and that the steel and phosphor-bronze cones are pressed on to the steel core and on to the external surface of the conductor respectively without any relative longitudinal movement. It is imperative to avoid any "birdcaging" of the copper wires during assembly in the clamp, and during erection generally.

Regarding cone-type fittings generally I would say that, provided the features mentioned in connection with steel-cored copper are incorporated in the fittings, and provided also that the device used for compacting the cones gives adequate pressure, experience shows that cone joints give unfailing performance, mechanically and electrically. They are sometimes criticized because a certain amount of care is needed to assemble them; this also applies to the joint described in the paper, particularly with steel-cored copper, where allowance has to be made for the creep. How can one be sure, even with a plain copper conductor, except by care in fitting, that the conductors have been fully inserted before compression? The assembly and compacting of most cone-type joints can be checked before coupling the halves together.

Mr. C. O. Boyse: Regarding the mechanical properties of copper conductors, I support Mr. Harding's suggestion that it would be simpler to deal with inelastic stretch by making an equivalent adjustment to the erection temperature. Fig. 2 shows that the permanent elongation corresponding to a change of stress from erection conditions to half breaking load is about 0·0003 in/in. Assuming a coefficient of expansion of 0·00000922 per deg F, this is equivalent to a reduction in erection temperature of 32·5 deg F. The objection to this procedure is that although it is accurate enough when applied to fairly deep sags, it may sometimes lead to appreciable errors because it ignores the fact that the resulting increase in erection tension itself reduces the amount of compensation necessary.

It does not appear at first sight that the percentage sag adjustments given in the last paragraph of Section 2.1 are

correctly derived from Fig. 2, but investigation shows that the apparent discrepancies are caused by the difficulty in making accurate measurements on the small scale reproduction of the stress-strain diagram. Perhaps the authors could make available to those specially interested larger copies of the diagram suitable for commercial use.

Under the V.D.E. regulations in force on the Continent, the maximum working conductor tensions are related to what is known as the "endurance limit" of the material. This limit is in no way connected with vibration fatigue, and is defined as the stress which a material will withstand for a year without breaking. A figure of 75% of the ultimate strength is given for copper, and I would like to ask the authors if they consider this to be a reasonable value of stress up to which copper conductors could be assumed capable of resisting indefinitely stress changes corresponding to weather variations.

Mr. K. L. May: After some twenty years' experience of most of the conductors detailed in this paper I give the following order of preference: copper, cadmium-copper, Copperweld, steel-cored copper, and, lastly, steel-cored aluminium.

One of the undertakings with which I am concerned, last year replaced by cadmium-copper a 7-mile steel-cored copper line of 0·04 in^2 copper equivalent (12/·064 in copper/7/·064 in steel) erected about ten miles from the sea coast. This line had stood for ten years and the s.c.c. conductors had to be removed on account of corrosion. The steel was not protected by the tape to which the authors refer, but it was initially heavily bitumenized. The experience of most of our companies tends to show that a period of 10 years or thereabouts is a critical time for these composite conductors. Generally speaking, the authors' tests rise to about 10 years, and although the figures they give are apparently very satisfactory, I wonder what will happen if another 5 years is added, because once corrosion starts it seems to proceed at a very rapid rate. I think the authors will agree that, although they have devoted so much space to steel-cored copper, they do not suggest that it should replace copper on any line where copper could normally be used.

I wish the authors had included a cautionary note as to what should be done in connection with vibration on most of these composite conductors and also on heavy copper conductors. There is a belief that copper is not subject to vibration, but the practice of working down to the Commissioners' minimum permitted conditions for heavy conductors gives a ratio of normal line tension to breaking load at 40° F of approximately 3 to 1. I think this is much too tight; hence on our 0·2 in^2 copper lines we have increased this ratio to 4 to 1, either by assuming an ice loading of ½ in instead of the present regulation of ⅜ in, or by increasing the factor of safety in the sag calculation. We have had no trouble so far with the 0·2 in^2 copper erected in this way. My suggestion is that 4 to 1 is a reasonable ratio to keep copper free from all vibration troubles, and I should appreciate the authors' confirmation.

To deal with the elongation of conductors, a common practice is to pull them up to roughly 60% of the ultimate strength and leave the load applied for 15 to 20 minutes. We have followed that practice for 15 years, and our maintenance engineers find that the regulation of the line remains quite satisfactory. It seems to me that the last paragraph of Section 2.1 should be supplemented to make it clear that the term "span" for this purpose means equivalent or basic span, because if individual span lengths were referred to the theory could not be put into practice.

Mr. H. W. Grimmitt: I agree with Mr. May in his advocacy of pre-stressing; it eliminates doubtful calculations.

Conductors between 0·075 in^2 and 0·15 in^2 inclusive, whether of copper, other metals or composite metals, give very little trouble when erected according to the Regulations in force in this country. Troubles with conductors have occurred chiefly outside the above range, owing to the fact that the Regulations require a loading of ⅜ in plus a wind pressure of 8-lb/ft^2, which is unsuitable for both the smaller and the larger conductors. The smaller ones are too slack at normal temperatures, and the large ones are a little too taut.

I am at the moment more interested in the smaller conductors. Two or three years before the war, all sorts of composite metal conductors were being designed and different types of stranding were much in vogue; now after about six years there has been some corrosion and vibration trouble. I have always favoured copper, either solid or stranded, and I do not think that any real economy is effected by the use of composite metal conductors; that is for the sizes below 0·075 in^2.

I should like to ask the authors if they have had any experience of vibration on the smaller cadmium-copper conductors that are supported on pin insulators. It was generally recognized that there would be no trouble with conductors on pin insulators.

Use of Copperweld conductors has never been given a fair opportunity in this country; I believe that this type of conductor is the complete answer to the problem of the larger conductor, and also for smaller conductors where large spans are essential.

Mr. W. J. Clements: I am surprised to find from Fig. 3 that the rate of softening and the point at which a rapid drop occurs are approximately the same for copper-cadmium and copper. I should have thought that the difference would be much more marked, and that copper-cadmium would resist softening to a much greater extent than copper. The authors refer to 80° C as a reasonable maximum for long periods, if any definite softening of copper is to be avoided. This seems to me to be on the high side for some brands of copper. It is also stated that the tensile strength of copper-cadmium conductors is 50% greater than that of copper conductors. For 0·050 and 0·066 in dia, this is correct, but in the larger sizes it is less; for 0·252 in dia the increase in strength is only 33%.

A cadmium content of 0·8 to 1·0% is quoted, and this, I imagine, refers to the amount added in alloying, but I should like the authors to confirm this. There is normally an appreciable loss of cadmium in the melting furnace, and the residual cadmium content may be about 0·6 to 0·7%. Similar mechanical and electrical properties can be obtained by adding 0·65% of cadmium and a small amount of other alloying material.

The elimination of galvanizing, although not important from the theoretical point of view for preventing corrosion, has one practical disadvantage. It is almost certain that ungalvanized steel wire suffers some corrosion during transit and storage before it is put in the cable, and, this action having started, it will very likely continue after the cable is completed and put into service.

A point which may be of interest in connection with Copperweld is that there is a limit to the diameter to which it can be drawn and the continuity of the copper covering guaranteed. With 30% material this diameter is 0·104 in, and with 40% it is 0·080 in. Below these sizes the copper coating is so thin that it is not possible to be sure that the steel is not exposed in some places. With another quality of Copperweld, the extra high tensile grade, not referred to by the authors, the limiting diameter is 0·128 in, since excessive cold work cannot be applied without further heat treatment, which itself cannot be carried out without detriment to the copper covering.

Recently I heard of a steel cable suspended at a given sag, which became gradually smaller with time. Investigation showed this was due to corrosion of the centre wire of the cable causing the cable to expand and shorten the lay of the cable by internal pressure. Have the authors had a similar experience?

Mr. W. J. Nicholls: I should like to join with previous speakers in hoping for a return to the pre-stressing of conductors in this country, instead of pulling them up a little too tight and hoping that they will go down when the first snowstorm occurs. Would the authors recommend over-tensioning or pre-stressing for steel-cored copper conductor?

On the question of steel-cored copper conductors and Tables 2 and 3, it is anomalous that in Table 2 the best results are obtained from samples 10 to 16, while the authors recommend sample 9. I think that they are probably very wise in stating that time alone will prove whether steel-cored copper conductor with a taped core will resist corrosion.

With regard to joints, I do not want to be discouraging in view of the good work which the authors have done in the elaborate testing and development of joints, but I do think that they have been a little over-zealous in saving metal. The cadmium-copper joint which has to withstand a load of about 7 tons is only 12 in long and gives a grip of only 6 in; the whole of that 6 in cannot be used, because the ends cannot be compressed fully. On test it has proved perfectly satisfactory, and I have no doubt that any number of repeat tests will give the same result, but field conditions call for a longer joint to allow for any bad workmanship.

Looking at the other joints for steel-cored copper in Fig. 12, I consider the best joint for field use is (*e*), where there are no ferrules. This joint is more difficult to manufacture, but allowance must be made for the careless man or the man in a hurry to repair a line who forgets to put a ferrule in, so that there is no grip on the steel. This may not be discovered for months, but with the first snowstorm the conductor will come down. The last joint shown has the disadvantage of ferrules. I do not like bending back the steel core, which in the steel-cored copper conductor is usually high-tensile steel, thereby weakening the strands at the point where the load may be greatest.

Mr. E. W. W. Double: I should like to comment on two points which have arisen during the discussion: (1) the eddy vibration of overhead lines, and (2) the pre-stressing of conductors. Laboratory and field tests reported in the U.S.A. and Germany show that vibration is reduced by the use of a three-stranded or triangular-shaped cross-section of conductor. The eddies initiating vibration seem to be more readily formed with the ordinary circular cross-section, particularly if the diameter is large. It should be remembered, however, that conductors with cross-sections unfavourable to vibration may suffer from greater corona effects, and greater wind and ice loadings.

Comparative tests carried out by the E.R.A. show that those increases of line sag which normally occur after the erection or stringing of the conductor can be reduced by pre-stressing, i.e. by first applying a very high tension. This operation gives the individual wires an opportunity to bed-in quickly, and unless the pre-stressing tension is exceeded at a later date, the subsequent increases in normal sag will be small. Hence from the standpoint of reducing increases in sag it is advisable to pre-stress before final stringing. The pre-stressing tension should be as high as possible within the limits of safety, and should be maintained for as long as is practicable.

Mr. A. W. Allwood (*communicated*): After many years of experiment with various types of overhead conductors made of different materials, experience appears to indicate that copper is the most capable of meeting the onerous conditions under which such conductors have to operate. It has a high resistance to atmospheric corrosion, even when industrial contamination is present, and has the advantage that it can be easily tapped without special provision to avoid electrolytic action. In this respect it scores over aluminium for rural distribution lines since, although bi-metallic connectors are available, there is always the risk that impurities in the metal may give rise to corrosion due to electrolytic action. Pure copper, however, has the one disadvantage of a low tensile strength and this, in general, means comparatively short spans for the smaller size conductors. This matter is of importance in an agricultural district, particularly if the undertaking is accustomed to paying fairly high wayleave rentals. The disadvantage is overcome by the use of cadmium-copper or by steel reinforcement. Of these two, it appears that the cadmium-copper conductor, having the advantage of being homogeneous, is the more satisfactory. This alloy lends itself to a very economical form of construction and is, in my opinion, in every way preferable to plain copper for the light lines used in rural distribution.

There is every reason to suppose that the improved methods which have been devised to eliminate corrosion in the steel cores of steel-cored copper conductors should be satisfactory, but it seems that the cost of the core protection is likely, in the smaller sizes, to raise the cost of the conductor to that of the equivalent in cadmium-copper, or even higher. In the undertaking with which I am associated it has been found uneconomical to erect a cadmium-copper or copper line with conductors smaller than 0·022 in^2, owing to the necessary reduction in span length. It very often occurs, however, that a smaller copper section would be satisfactory for supplying loads at isolated premises. There does, therefore, seem to be a distinct field for a conductor of high tensile strength having a copper equivalent area of about 0·01 in^2, and it is in this connection that the authors' remarks on Copperweld conductors are very interesting. Unfortunately, in the past, there has been a certain amount of confusion between Copperweld conductors and other copper-clad steel conductors manufactured by a totally different process. Some of these latter have given trouble owing to the copper flaking off the steel, and in due course corrosion of the steel itself has followed. This, we are assured, cannot take place with the Copperweld conductors. What is really required is a reliable conductor which will enable a light line to be erected on medium wood poles and have a maximum span length of between 500 and 550 ft. If such a conductor can be designed it will be possible to construct light rural lines on a much more economical basis than if plain copper conductors are used.

Mr. W. F. Bowling (*communicated*): The authors suggest that when overstringing during erection to compensate for subsequent permanent extension of the conductor, a separate sag calculation should be made for each particular span based on the increase of conductor length as obtained from tests. Permanent extension is similar in effect to an increase of temperature. If the permanent stretch per unit length of conductor be divided by the coefficient of expansion of the conductor, a temperature increase may be obtained which would give the same sag increase as the permanent stretch. Using this method, standard sag-tension curves can be employed, the particular sag and tension for erection being those corresponding to the corrected temperature. For stranded copper conductors of normal sectional area, this correction is usually between 25 and 30° F. I believe that this method is more satisfactory than that suggested in the paper of reducing the sag by a percentage; for, as the authors indicate, this varies with span length and size of conductor.

Mr. A. Burke (*communicated*): Unless the copper is known to be rich in silver, the authors' temperature limit of 80° C for long periods does not appear safe. Zucker* states that crystal growth, which weakens the wire, commences when the loss in strength reaches 5%, and curve (*b*) in Fig. 5 shows that copper with quite a good silver content reaches this condition after two months. According to Zucker's paper, a reduction of silver

* "Thermal Rating of Overhead Line Wire," *Transactions American I.E.E.*, 1943, 62, p. 501.

below 0·002% is not unimportant, and in fact with no silver the permissible temperature must be at least 50 deg C lower than with 0·002%; on the other hand, increase in oxygen above 0·025% has a negligible effect. Fig. 6 is misleading since it suggests a superiority for cadmium-copper which cannot be enjoyed owing to ground clearance and losses. Will the authors say how the oxygen and silver contents affect the annealing temperature of cadmium-copper?

In practice, the question of damaging the conductor by load current would never arise in peace time, and there is little danger at any time. There is, however, quite a possibility of weakening by short-circuit current. The type of protection used normally cuts off the current in time on higher-voltage lines, but there is a grave probability of danger with light 11-kV lines connected to large substations. The matter is important for light-conductor rural lines, particularly when automatic-reclosing switches are employed. In view of the short duration, the authors' curves are not applicable. Schmitt's* investigation gave valuable results, but the influence of impurities was ignored. Altogether the data available are disquieting, but not illuminating. There is need for tests to determine the effects of variation in cold-working, impurities, duration of and stress during heating and on repeated heating at intervals. The appropriate B.S. should grade the materials according to their annealing temperature, since otherwise it is difficult to know whether one is safe or not.

The authors throw no new light on the problem of forecasting the temperature likely to be attained under working conditions. Will they quote their authority for the statement that solar absorption is negligible, bearing in mind that 50° C is the normal maximum temperature? Tests† in Switzerland on white and dark-brown insulators showed rises of 14·8 and 28·7° C respectively over an ambient temperature of 28° C. The dark-brown or black weathered surface of copper would appear to be excellent for absorbing radiant heat. It is agreed that the wind velocity is seldom less than 1 m.p.h., but do the authors hold that their curves apply when its direction is along and not normal to that of the line?

Mr. E. C. Neate (*communicated*): Due to present conditions, the paper deals only briefly with a number of conductors not in common use in this country. It would have been helpful had a bibliography been provided. For example, detail characteristics of "H.H." conductor and Copperweld in a number of different sizes are available in the American "Standard Handbook for Electrical Engineers."

I do not agree with the statement in Section 5.1 that steel-reinforced copper presents no difficulty in handling or erection. Due to the bedding down of the copper strands into the tape there is a considerable change in the characteristics. Little information has been published as to the non-elastic extension of this conductor, and satisfactory results can be secured only by adequate over-tensioning. The time for loading is certainly more than the one or two hours suggested in Section 2.1. I would suggest a period of 48 hours, although this time depends to a large degree on the nature of the compound and consequently on the ambient temperature. This type of conductor is more liable to "birdcage" than plain or cadmium-copper strand.

During the past ten years, I have not heard of a failure of any cone-type joint when used on homogeneous conductors. The trouble appears to be associated with composite conductors and to be one of many. Unless the cost of cadmium rises to prohibitive heights, it would seem difficult to establish a case for composite copper conductors.

Mr. G. S. Sloan (*communicated*): The authors do not make clear how the lower modulus of elasticity should be used in calculating erection curves, having regard to the fact that such curves are based on the stress in the conductor when under specified ice and wind load. Their suggestion is correct when the proper tension at one particular erection temperature has already been determined, and it is merely a question of finding corresponding tensions at other erection temperatures. Careful tests show that the return curves are not always straight all the way down as shown in Fig. 1, but bend back towards the origin at very low stresses. Furthermore, the slope of the next run up is then slightly less steep. The extension of 0·11% for 0·16-in dia. hard-drawn copper wire implies a modulus of elasticity of 28×10^6 lb/in^2 on the assumption that the loading was from zero to 50% of its tensile strength. The authors' comments would be appreciated.

Limited tests in which I have participated indicate that it may not be safe to rely on Fig. 2, and hence that the assumption of 0·04% for the permanent extension up to 50% of the ultimate strength may not be well founded. One test on 7-strand 0·025-in^2 copper conductor was as follows: It was first stressed in 15 steps up to 75% of its ultimate strength, the stress being reduced to less than 25% between each step. It was taken down, coiled, and left for over two years, after which it was again loaded to 75% of its ultimate strength, showing an immediate permanent extension of nearly 0·03%, which increased to 0·055% after two days, when extension had practically ceased. On unloading and reloading there was a slight decrease in extension, but after five days there was an increase of 0·025%, when extension had again ceased. Two repetitions of the loading and unloading with two days in between brought a further increase of 0·0085%. These tests confirm the authors' statement that extension practically ceases after a short time, but they also show that further increases occur on unloading and reloading; there is also a clear indication that long-term relaxation has a big effect in permitting further extension. It should be noted that the maximum stress was 75% of the ultimate, as in Fig. 2, and it is not certain what the result would be if the stress did not exceed 50%. In the N.P.L. tests,* where 50% was not exceeded, the permanent extension was 0·08% for a stranded conductor, but only 0·02% for a single wire. Our tests indicate that the number of strands affects the results.

I agree that the ultimate modulus is more nearly 17×10^6 than 18×10^6 lb/in^2 as found by the N.P.L. tests referred to above. This discrepancy confirms that sufficient is not yet known about the problem, and that even well-authenticated results should not be accepted as universally correct without qualification.

* "Uber den Einfluss von Kurzschluss-strömen auf die Festigkeit und Leitfähigkeit hartgezogener Drähte," *Elektrotechnische Zeitschrift*, 1928, 49, p. 684.
† "La couleur des isolateurs utilisés en plein air," *Bulletin Association Suisse des Électriciens*, 1928, 19, p. 677.

* "Report upon Tests on Hard-drawn Copper Wires and Cables for Overhead Transmission Lines," *Journal I.E.E.*, 1923, 61, p. 997.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Mr. G. W. Preston and Dr. H. G. Taylor (*in reply*): We shall first reply to questions relating to the calculation of erection sags which have been raised by several contributors to the discussion.

Messrs. Harding, Boyse and Bowling suggest that the simplest way of determining erection sags for an unstretched conductor is to treat the permanent stretch as a thermal variation of length and obtain the erection sag and tension from the normal design curves by merely assuming a reduction of erection temperature. They would appear, however, to have overlooked the significance of the change in modulus which takes place when a conductor is

first loaded. The tension in an initially unstretched conductor for any given sag at the time of erection is not the same as the tension in the conductor at the same sag after it has been subjected to maximum loading. The method of calculation suggested would not give the correct erection sag and would overcompensate for stretch.

As suggested by Mr. Boyse, we shall be glad to make available larger scale copies of Fig. 2, if required, but we cannot agree that there are any apparent discrepancies in the percentage sag adjustments given in Section 2.1. The figures quoted can be derived from information given in the text, if necessary without referring to Fig. 2, provided that the correct method of calculation is adopted.

In reply to Mr. Sloan, it is not possible within the space available to explain how erection sag calculations should be made employing the lower modulus of elasticity. It is quite a simple matter, and details can be obtained from the published literature.

Our replies to other questions raised are as follows:

Dr. Miller.—A bibliography was not included as no time could be found to prepare one. To be at all comprehensive it would have been extremely long, and there are other sources from which appropriate references can be obtained.

Limitations of space prevented a discussion of the effects of tellurium and selenium in copper. In the amounts in which these elements may be expected normally to be present in high-conductivity copper, we do not think they have a pronounced effect on its properties. According to Smart and Smith,* the effect of small quantities of tellurium on the softening temperature of high-purity copper is greater than that of equal quantities of silver, but in no case would we expect tellurium normally to be present in amounts equal to silver. As far as we are aware, the effect of small quantities of selenium on the softening temperature of copper is not at present known.

We agree that in most practical cases a temperature of 80° C is not likely to be attained. We have no faith in accelerated laboratory corrosion tests.

Mr. Harding.—We do not know of any line tests with hollow conductor type (C) in Fig. 7. The conductors in the corrosion tests described in Section 5 were not carrying current, but were subjected to normal atmospheric changes of temperature.

Mr. Boyse.—We assume that the V.D.E. "endurance limit" referred to means that at 75% of its breaking load a hard-drawn copper conductor will not creep indefinitely and could maintain the load stated for a period of one year without failure. A reference to Section 2.1 shows that this is a reasonable assumption. We consider 75% of the breaking load too high as a normal working stress under overhead-line conditions when wind effects are always present.

Mr. May.—The corrosion tests are continuing, and we hope to be able to provide in five years' time further evidence to allay the fears expressed by Mr. May. We certainly do not suggest that steel-cored copper should replace copper on any line where the latter can normally be used. We agree that a 4 : 1 tension ratio is a reasonable safeguard against vibration trouble.

Mr. Grimmitt.—There have been isolated cases of failure of small size cadmium-copper conductors on pin insulators, due to vibration. We prefer a 3-wire stranding in the smaller sizes, and if these are properly bound in, preferably in the top groove of the insulator, and are not overstressed, we should not anticipate any widespread trouble.

Mr. Clements.—We agree that in general the residual cadmium content of cadmium-copper for line conductors is between about 0·6 and 0·8%. We have not heard of the sag of a conductor decreasing owing to a shortening of the lay, but conceive it to be possible.

Mr. Nicholls.—Without further experience we would hesitate to express any definite preference for either over-tensioning or pre-stressing with steel-cored copper conductors. Each method has its advantages and disadvantages. The object of reducing the length of the compressed sleeve joints was not primarily to save metal, but to save weight, cost and time in making the joint.

Mr. Allwood.—As an alternative to the use of a high-strength copper alloy, reinforcement with Copperweld is the only really satisfactory method at present available of increasing the tensile strength of the smaller sizes of stranded copper conductor. Where a copper sectional area as small as 0·01 in^2 is required with high strength, we agree that Copperweld alone provides the best solution. Copperweld conductors in America have amply proved their value for rural electrification.

Mr. Burke.—We are familiar with the paper by M. Zucker. In our view a number of the deductions made in it are not warranted by the evidence on which supposedly they are based. We are not aware of any evidence sufficient to justify the figures or the conclusions regarding the effect of silver which Mr. Burke derives from the paper in question.

We do not agree that Fig. 6 as presented in the paper is misleading.

Cadmium is itself a deoxidant, and therefore the effect of varying oxygen content on the annealing temperature of the normal type of cadmium-copper does not arise, since the alloy is substantially free from oxygen. We would expect the effect of silver, in the small quantities in which it is likely to be present as an impurity, to be negligible in copper containing cadmium in the percentage normally added to make the alloy.

We do not state in the paper that solar absorption is negligible, but that its effect decreases with rising conductor temperature and becomes negligible at relatively high temperatures. The paper deals with temperatures of 80° and 150° C. For all practical purposes, we believe that the effect of solar absorption at such temperatures is sufficiently small to be neglected. With reference to the direction of the assumed 1-m.p.h. wind, we think Mr. Burke is being too precise. In theory the loadings shown would not apply if the wind were along the line only.

Mr. Neate.—The periods of stressing for test purposes to remove permanent stretch, referred to in Section 2.1, were not intended to apply to a conductor with a wrapped steel core under line-erection conditions. Owing to enforced abbreviation our remarks on the shortcomings of cone-type joints may be rather misleading. We agree that cone-type joints on ordinary copper or copper-alloy conductors have given satisfactory service.

Mr. Sloan.—We would quite expect that a stranded conductor taken down after loading, coiled and stored, would show some further apparently non-elastic extension when re-stressed. Mr. Sloan does not make it clear whether the length of the conductor he tested showed a progressive increase in length or whether there was some recovery after each loading. In the creep tests in Section 2.1 the initial extension of 0·11% was not elastic extension. A modulus cannot therefore be derived from it. The figures quoted by Mr. Sloan as being taken from the N.P.L. tests have apparently been derived from the results of single experiments carried out on 100 yd of one size of stranded conductor and on 10 in of single wire. We are not surprised that the figures do not agree more closely.

* "The Effect of Fifth-period Elements on the Properties of Copper," *Transactions of the American Institute of Mining and Metallurgical Engineers*, 1943, 152, p. 103.

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RESTRIKING VOLTAGE AS A FACTOR IN THE PERFORMANCE, RATING AND SELECTION OF CIRCUIT-BREAKERS

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SUMMARY

Experience in service and at short-circuit testing stations has demonstrated that the behaviour of circuit-breakers when breaking short-circuit currents depends on a number of factors which have been termed conditions of severity. They include circuit power-factor, recovery voltage, earthing conditions, and current asymmetry, and are specified in certain clauses in current testing specifications.

The paper deals with a further condition of severity which has been acknowledged but is not specified in specifications, namely the re-striking-voltage transient and its important controlling attribute, the rate of rise of restriking voltage. The aim of the paper is to place this severity factor in its correct perspective by stating its effect on the performance of plain-break oil circuit-breakers, oil circuit-breakers fitted with arc-control devices, and air-blast circuit-breakers. Compared with the relatively small effect that rate of rise has on plain-break and arc-control oil breakers, the importance of the effect of rate of rise on the performance of air-blast breakers is emphasized, and recommendations are made as to the utilization of this important factor in the rating, testing and selection of these breakers.

A method is proposed for testing certain types of high-voltage air-blast breakers whose breaking capacities are above those for which testing stations are normally equipped.

(1) INTRODUCTION

The phenomenon of breaking an alternating current by a circuit-breaker is governed by the current being interrupted at zero value, the voltage re-establishing itself across the circuit. This re-establishing voltage is known as the restriking-voltage transient and has an important influence on the performance of certain types of circuit-breakers.

B.S. 116, Parts I and II, and the I.E.C. specification for oil circuit-breakers correctly define and specify the well-known factors controlling circuit severity, including circuit power-factor, recovery voltage, earthing conditions, and current asymmetry. This paper deals with the further important factor of restriking voltage. The chief factors governing the amplitude of the re-striking-voltage transient are stated in the above specifications; but, owing to the limited knowledge available when they were drafted, the rate at which the voltage re-establishes itself is merely mentioned and not specified.

The introduction into circuit-breaker testing technique of the cathode-ray oscillograph has contributed appreciably to our knowledge of a.c. arc phenomena, while the results of extensive short-circuit tests on various types of oil circuit-breakers and on air-blast circuit-breakers have given a clear conception of the relative bearing of restriking voltage on performance.

The bearing of restriking voltage on standardization proposals in respect to rating, testing, and selection of high-voltage circuit-breakers is outlined.

Lower-voltage circuit-breakers, such as those of the air-break type, are excluded from the paper as the arc phenomena are of a different character. In these breakers, the arc voltage is a high proportion of the circuit voltage and instability of the arc may prove a more important determinant of behaviour than the restriking voltage.

(2) GENERAL

(2.1) Restriking-Voltage Transient

B.S. 116 defines the restriking voltage as a high-frequency transient voltage that exists at, or in close proximity to, each current zero pause during the arcing period, the important attributes being the amplitude and the rate of rise (expressed in V/μs) at the moment of arc extinction.

Since the restriking voltage is not always a high-frequency transient this definition is not sufficient for general use; it is, however, applicable to the testing of circuit-breakers, and for our purpose is taken as the voltage varying with time that appears between the contacts of a circuit-breaker immediately after the current has been interrupted.

As the breaker at the moment of final arc extinction can influence the shape of the transient voltage recorded,[3] it is essential to differentiate between the inherent restriking-voltage transient of the circuit and the restriking voltage recorded during circuit-breaker tests.

The simplest form of inherent voltage transient is a single-frequency damped oscillation (Fig. 1). The rate of rise of restriking voltage is usually interpreted in this country and in the United States by a line drawn from the origin tangential to the initial peak, its slope being expressed in V/μs.

Two modifications which frequently arise in practice are shown

* A. Reyrolle & Co., Ltd.

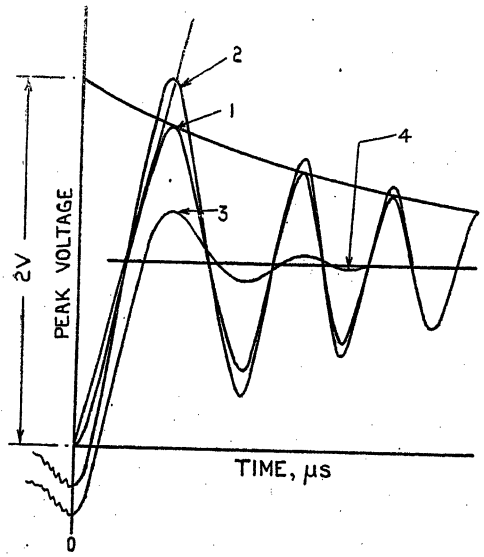


Fig. 1.—Diagram illustrating the influence of the circuit-breaker on the circuit inherent transient.

(1) Inherent transient.
(2) Effect of arc voltage.
(3) Effect of high post-arc conductivity.
(4) Peak recovery voltage (system frequency).

in Fig. 1. In one case the inherent transient amplitude is increased above the normal, and in the other the initial peak is much reduced.

When considering the conditions of circuit severity during test or at any location in a network, the necessity of basing a statement of severity on the inherent transient will be evident. It is necessary, therefore, to define this transient, and the following definition is suggested:

> "The inherent restriking voltage is a voltage varying with time that would appear between the contacts of a circuit-breaker immediately after the interruption of the current in the circuit, under the ideal conditions that the circuit-breaker in no way alters the transient phenomena and that interruption occurs when the circuit has a zero d.c. component and 100 per cent recovery voltage."

The necessity of a specification covering standardized methods of calculating and assessing this inherent rate of rise (R.R.R.V.) will be apparent. Draft clauses have been prepared for consideration by the I.E.C., but this work has been deferred by the war.

(2.2) Classification of Circuit Transients

Restriking-voltage transients, and consequently their respective circuits,[4] can generally be placed under three main headings, namely:—

(1) Single-frequency oscillatory transients
(2) Double-frequency oscillatory transients
(3) Non-oscillatory transients

Combinations of these types are experienced, but the treatment of such combinations is usually covered by resolution into the above elementary types.

Examples of typical inherent transients recorded by the restriking-voltage indicator[5] and details of the equivalent circuits are shown in Fig. 2, columns (A) and (D). Columns (B) and (C) indicate how a particular transient may be modified, de-

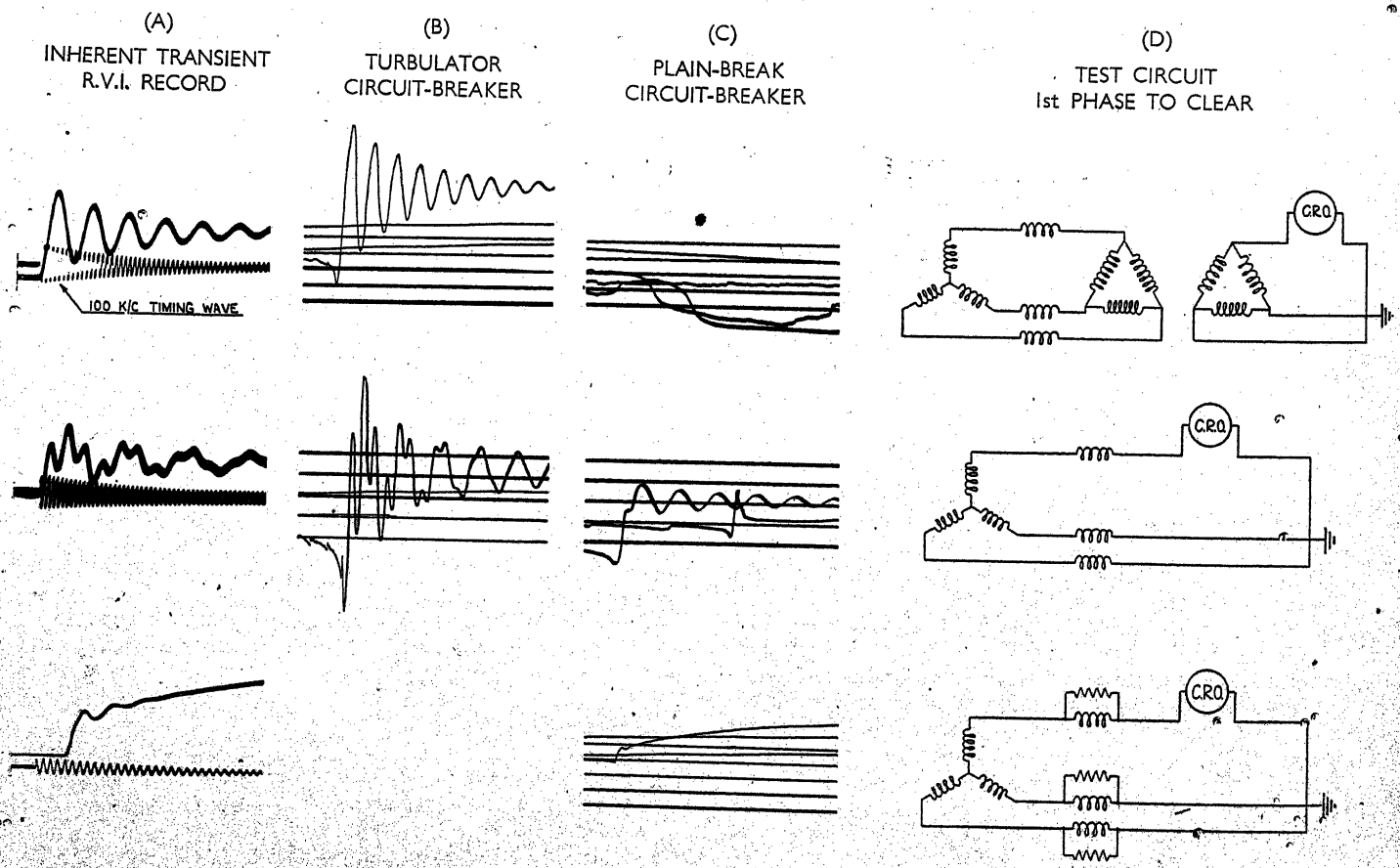


Fig. 2.—Restriking-voltage transients for typical circuits, recorded on the first phase to clear for different test conditions.

pending on the type of circuit-breaker employed. The circuits employed at testing stations and the various circuit-breaker location points on supply companies' systems can usually be resolved into one of these standard forms, enabling an assessment of restriking-voltage severity to be made on some agreed standard basis in line with the above classification.

(3) PHENOMENA OF ARC EXTINCTION

A "break" operation by a circuit-breaker creates an arc which is controlled until a current zero is reached when arc extinction can take place. This extinction depends upon the de-ionization of the residual arc path at current zero and the ability of the dielectric condition to withstand the restriking-voltage transient which appears after current ceases to flow. To be able to control this de-ionization in the least possible time various devices have been introduced in different types of circuit-breaker.

Our knowledge concerning this critical period in the rupturing of the arc has greatly expanded in the last few years, but it is still not complete. At the same time, the various types of breakers in use, e.g. plain-break oil, arc-controlled oil, and air-blast breakers, etc., have very different de-ionizing characteristics. Consequently, no generalization of zero-pause phenomena of universal application is practicable. No analysis of the de-ionization theories applicable to the different types of circuit-breakers is possible, but the ultimate result it is desired to achieve is the same, namely the establishment of a dielectric condition between the circuit-breaker contacts in the shortest possible time to prevent the arc restriking after current zero.

Two main theories have been advanced to account for the ability of the arc gap to withstand the restriking voltage. The first, and the simplest, is the dielectric-recovery theory; the second is the energy-balance theory.

(3.1) Dielectric-Recovery Theory

The familiar dielectric-recovery theory is based on the conception that the inter-contact space attains a dielectric condition during the zero-pause period which will withstand a certain voltage, the magnitude, the rate of rise and the duration of this voltage being a measure of dielectric recovery. Thus in oil circuit-breakers, decomposition and carbonization of the oil take place during each arcing loop, these changes being accompanied by ionization of the gas and vapour in the vicinity of the arc column. Control of the degree of ionization at current zero is obtained by adopting methods for effecting and aiding de-ionization.

Valuable information of the rate of dielectric recovery is obtained by measuring the transient voltages recorded at each arcing-current zero up to and including the final clearance. Analysis of a series of such records enables the values of the maximum dielectric-recovery voltage at which restriking just fails to take place to be ascertained for comparison purposes.

Fig. 3 gives dielectric-recovery curves for typical circuit-breakers, based on cathode-ray records obtained with the same test circuits. These indicate that the rate of dielectric recovery for final clearance is closely dependent on the type of breaker, and also that the characteristic shapes of these curves in respect to current broken are widely different. It may be concluded from these records that much more is involved than the mere attaining of a minimum electric strength, and that both the circuit conditions and the physical provisions made for promoting de-ionization play important parts.

(3.2) Energy-Balance Theory

A more recent theory[8] of arc extinction based on energy considerations has been advanced, and is a modification of the old

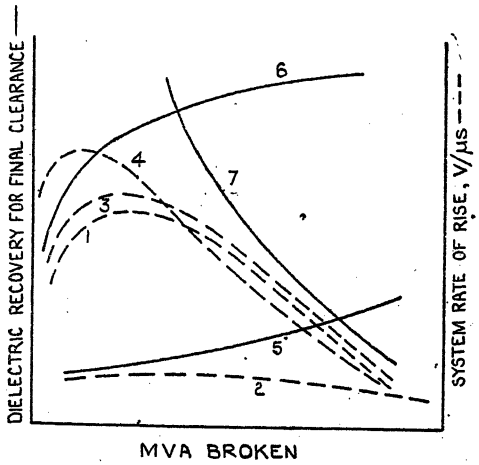


Fig. 3.—Diagram showing typical dielectric recovery characteristics for three types of circuit-breaker, together with curves showing the probable influence of these circuit-breakers on the system rates of rise.

Curve 1—Assumed boundary curve of inherent system severities for various MVA values.
Curve 2—Resultant severity that would be recorded when using plain-break oil circuit-breaker.
Curve 3—Resultant severity when using turbulator circuit-breaker.
Curve 4—Resultant severity when using air-blast circuit-breaker.
Curve 5—Apparent dielectric recovery curve of plain-break oil circuit-breaker (based on arc-extinction conditions).
Curve 6—Apparent dielectric recovery curve of turbulator circuit-breaker (based on arc-extinction conditions).
Curve 7—Apparent dielectric recovery curve of gas-blast circuit-breaker (based on arc-extinction conditions).

theory propounded for d.c. arc extinction. In this theory the physical conditions obtaining in the breaker in the vicinity of current zero are correlated with those of the circuit on the assumption that before arc extinction can be effected the energy dissipated by the process of de-ionization must be greater than the energy input from the circuit.

Whilst this theory aims at a comprehensive exposition of arc extinction for all conditions, the published results so far available indicate that before it can be effectively applied the physical features of each class of breaker and also those of the circuit must be fully known.

(4) INFLUENCE OF CIRCUIT SEVERITY ON CIRCUIT-BREAKER PERFORMANCE

As pointed out in Section 2, the type of circuit-breaker influences the shape of the restriking-voltage transient recorded, but conversely the shape of this transient governs the behaviour of the circuit-breaker, the extent of such influence depending on the type of breaker. For establishing this influence with various types of circuit-breakers, the main sources of information have been research and experimental test data, although the relative effects may also be noted in service when breaking with oil circuit-breakers under fault conditions. In general, on 3-phase breakers, the severity of the first phase to clear controls arc extinction, and this is implied in all future reference to the R.R.R.V.

(4.1) Plain-Break Oil Circuit-Breakers

In circuit-breakers of the plain-break type the arc is quenched in a static gas bubble produced by the decomposition of the oil; the de-ionizing effect is here probably caused by turbulence set up by gas and vapour from the walls of the gas bubble, especially from the zone towards which the arc stream is blown by the electromagnetic repulsion in normal designs of breaker. These gas bubbles have relatively high post-arc conductivities which

largely damp out transient phenomena with a frequency above a certain critical value.

The cathode-ray oscillograms in Fig. 2 reveal the pronounced damping obtained with a plain-break breaker. In view of the residual post-arc conductivity, which acts as a varying resistance across the capacitance-inductance combination of the circuit, any frequency above a certain value is damped out, with the result that no appreciable increase in arc duration is observed for the higher natural frequencies.

Fig. 4(*a*) shows the relative effects of restriking voltage on a

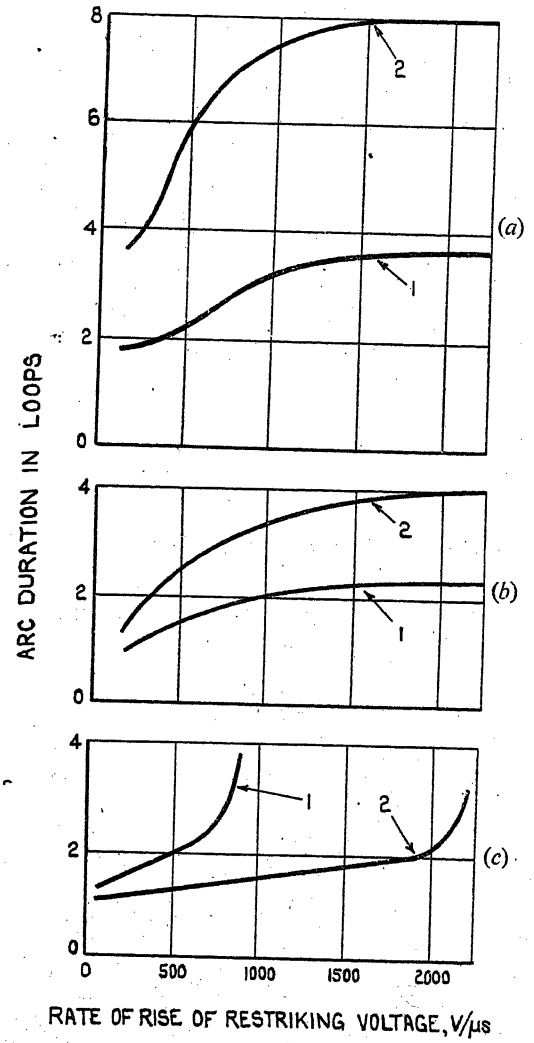


Fig. 4.—Influence of the restriking-voltage transient on circuit-breaker performance, based on boundary curves of arc duration. Curve (1) for 100% of rated MVA, and curve (2) for 10% of rated MVA.

(*a*) Plain-break circuit-breaker. (*b*) Turbulator circuit-breaker. (*c*) Air-blast circuit-breaker.

plain-break circuit-breaker, indicating that for R.R.R.V.'s above 600 or 800 V/μs there is relatively little increase in the duration of the arc. This observation is borne out by many investigators and is the reason why the R.R.R.V. has not been a vital item in the standardization of oil circuit-breakers, for testing-station conditions adequately cover the worst possible service conditions.

(4.2) Oil Circuit-Breakers with Arc-Control Contacts

These circuit-breakers embody arc-control contacts, of which the "turbulator" is typical; in these the high gas pressure generated by the arc is confined to a small arc chamber. The arc is carefully positioned relative to the side vents to enable the residual path to be de-ionized by a stream of hot gases and vapour discharged at high velocity through the vents.

Turbulator pressures recorded on the oscillograms in Fig. 5A indicate that the gas pressure is built up inside the turbulator over a greater part of each arcing loop, thus producing a de-ionizing characteristic at the current zeros which increases in effectiveness with increasing short-circuit current. This class of breaker has a similar but improved characteristic as is shown in Fig. 4(*b*) where the duration of the arc is seen to be no more susceptible to rate of rise than the plain-break design.

The flat restriking-voltage/arc-duration characteristic of the turbulator breaker over the rate-of-rise range investigated is not due to post-arc conductivity (as can be deduced from Fig. 2), but to the extremely rapid manner in which this class of breaker regains the necessary dielectric strength in the arc cavity, thus providing an ample margin over likely restriking transients under service and testing-station conditions. Fig. 5B shows the process of arc extinction in the turbulator, and correlates electromagnetic and cathode-ray oscillograms.

(4.3) Air-Blast Circuit-Breakers

Air-blast breakers such as the high-air-velocity, axial-blast nozzle types, while differing in detail in design, closely resemble in basic features the type considered here. The operating pressure and the air-reservoir capacity are fixed by the rating, duties, and economic considerations, so that there is inherently an excess of air pressure for light switching duties as against that for the heavier duties.

Tests on these breakers indicate that they are highly sensitive to the rate of rise of restriking voltage. Fig. 6 shows a typical R.R.R.V./MVA characteristic of an air-blast breaker in which the nozzle diameter is fixed and the air pressure is kept constant irrespective of the current broken. This characteristic, which approximates to a rectangular hyperbola, indicates that at low MVA values the breaker can cope with higher R.R.R.V.'s than at high MVA values. If the rate of rise is increased above the value indicated for each MVA level, then the additional stress will produce a sudden increase in arcing time as shown in Fig. 4(*c*).

Unlike the other two types of breaker referred to, the performance of this type is dependent upon the R.R.R.V.

There are two ways of restricting the R.R.R.V. that can occur in a circuit-breaker: (1) by embodying a capacitor across connected apparatus or across the breaking unit of the circuit-breaker; or (2) by embodying a resistance unit which is connected during the arc-extinction period. Each is technically possible in most cases, although for outdoor high-voltage breakers neither is very attractive.

Resistance switching is practically essential for heavy-duty lower voltage breakers, but not for the higher-voltage breakers where R.R.R.V./MVA characteristics can be obtained with designs which can cope with ordinary conditions of service.

Where it is necessary to incorporate resistors, the choice of the ohmic value is governed by the following considerations:—

(*a*) The resistor should modify all transients so that the resultant rate of rise is not in excess of that which the breaker can deal with at any fault MVA value within its rating.

(*b*) For high-voltage breakers economic designs are possible even without resistors. Where resistors are employed they should be required to cut down only the higher rates of rise, hence the ohmic value should be relatively high, thus making accommodation possible.

(*c*) For lower-voltage breakers the resistance value must be

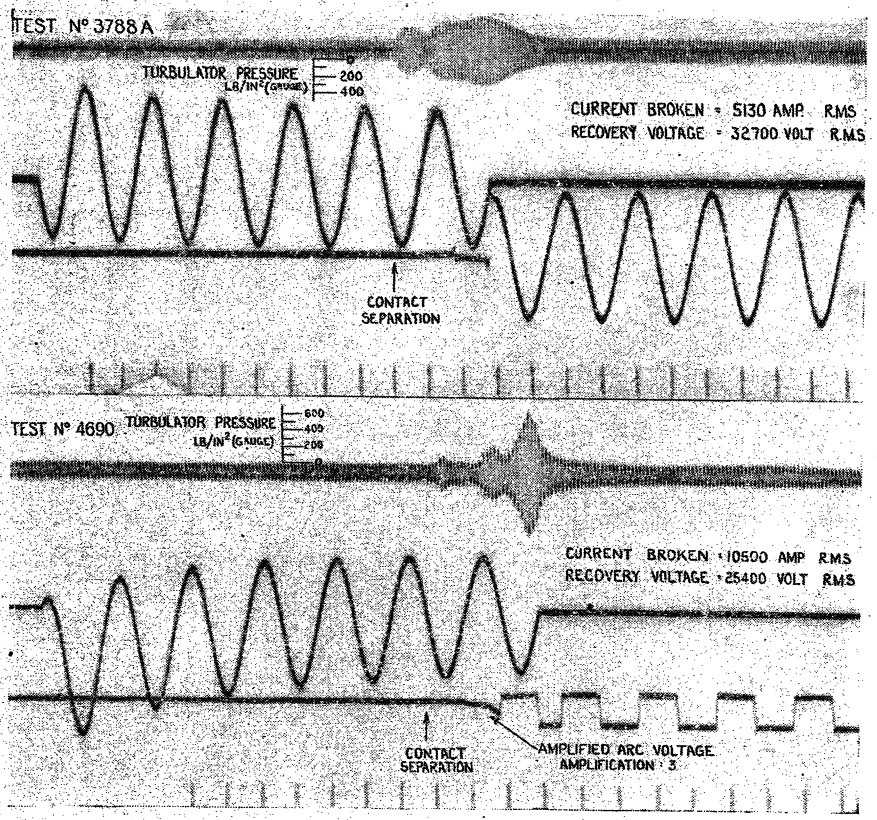


Fig. 5A.—Turbulator circuit-breaker characteristics, showing examples of the internal turbulator pressure correlated with current and voltage.

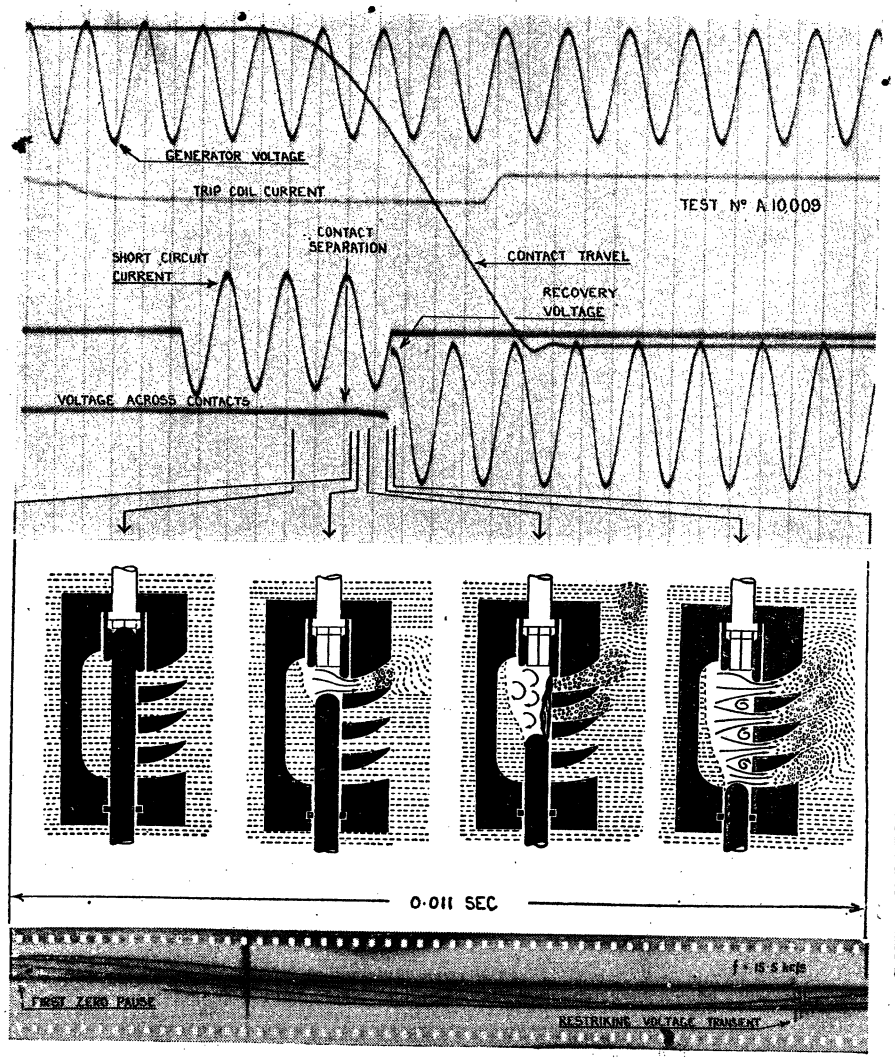


Fig. 5B.—Turbulator circuit-breaker characteristics, showing the process of arc extinction correlated with electromagnetic and cathode-ray oscillograms.

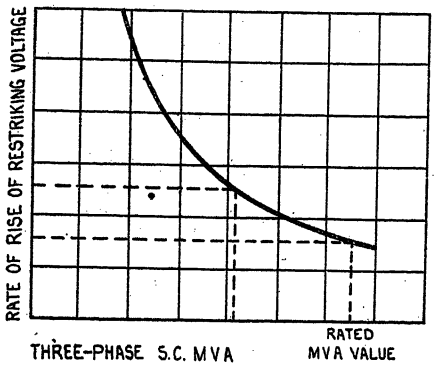


Fig. 6.—Typical air-blast circuit-breaker R.R.R.V./MVA characteristic. Boundary curve for satisfactory clearance for declared air pressure and rated voltage.

such that an economical design of breaking unit can be produced for the rating required.

(*d*) Methods of introducing the resistor into the circuit are: (1) by permanently connecting it across the breaker contacts; (2) by automatically connecting it through an auxiliary electrode during the operation of the breaker; the choice of resistance might be influenced by adopting this latter method.

One possible resistance value is given by:

$$R_c = \tfrac{1}{2}\sqrt{(L/C)} = \frac{1}{2\pi}\sqrt{(1/LC)} \,.\, \pi L = \pi f L,$$

where f is the natural frequency corresponding to the R.R.R.V. limit of the breaker at the short-circuit current (i) under consideration in the absence of such a resistor, and L is the inductance obtained from $V/(314 \times i\sqrt{3})$ where V is the rated voltage. This resistance is, of course, the critical damping resistance of a circuit of frequency f and inductance L. If this value is chosen, the breaker will deal with all rates of rise. If twice this value is chosen, any frequency above $2f$ will be critically damped, while frequencies below $2f$ will be damped sufficiently for their severity to be within the R.R.R.V. limit of the breaker. The effect at other MVA values will require verification, taking account of the breaker characteristics.

(5) REVIEW OF STANDARDIZATION IN RESPECT OF CIRCUIT SEVERITY

It is important to review the question of standardization in the light of the influence of circuit severity on circuit-breaker performance outlined in Section 4.

(5.1) Plain-Break Oil Circuit-Breakers

The I.E.C. specification and B.S. 116 both acknowledge that the R.R.R.V. has a bearing on circuit-breaker performance, but no attempt is made to assess a quantitative relationship and express this in the specification. It was appreciated by some members of the Drafting Committee that the characteristics of the oil circuit-breakers under discussion were such that the breakers would not be seriously affected by small variations of the R.R.R.V. at different testing stations, provided that current and power factor were controlled by reactances and resistors connected in series, and that no parallel combinations were used.

If the specification for the rating, testing, and selection of these circuit-breakers has to be revised, there will still be no real need to embody any further rate of rise conditions. This is confirmed by the very satisfactory behaviour of these breakers in industrial service over many years.

(5.2) Oil Circuit-Breakers with Arc-Control Contacts

The same remarks apply to these breakers, for which testing stations conforming with B.S. 116 or the I.E.C. specification employ R.R.R.V.'s in excess of those that appear to influence the characteristics of the breaker.

(5.3) Air-Blast Circuit-Breakers

Cognizance must be taken of the R.R.R.V. when testing all air-blast breakers, and with those not fitted with discharge resistors the rate of rise when rating and when selecting for service must also be taken into consideration.

The configuration of the contacts on these breakers is controlled by the voltage rating to a greater extent than in oil circuit-breakers, and wherever possible test conditions should therefore give the specified minimum recovery voltage across the breaking unit over the full current range. Tests as laid down in B.S. 116, Part II, do not entirely prove the suitability of the breaker for its rating. For certain designs, tests can be employed that take into account those characteristics and design features of the air-blast breaker which give a reasonable proof of adequacy in respect to performance.

When considering the R.R.R.V. in the selection of breakers, it is important that all aspects of the problem be borne in mind, and a simple basis adopted which avoids any risk of inadequacy.

(6) SERVICE AND TESTING-STATION SEVERITIES

With the appearance of air-blast circuit-breakers on the British market, the necessity of examining both service and testing-station severities arises.

Testing stations and system circuits can generally be resolved into the three distinct types indicated above; examples which give restriking-voltage transients complying with these classifications are shown in Fig. 2(*a*). In systems, the type of transients to be anticipated depends on the system layout, the location of the fault, and the point of clearance. Thus, even short lengths of cable can have a marked influence on the rates of rise caused by inductive apparatus; this is shown in Fig. 8.

At testing stations, the fault location and the circuit-breaker position are fixed, and consequently the circuit conditions are the only determining factors.

Methods of analysis for various typical system conditions are described in Section 11.2, which gives the rates of rise on the first phase to clear on 3-phase faults.

(6.1) Service

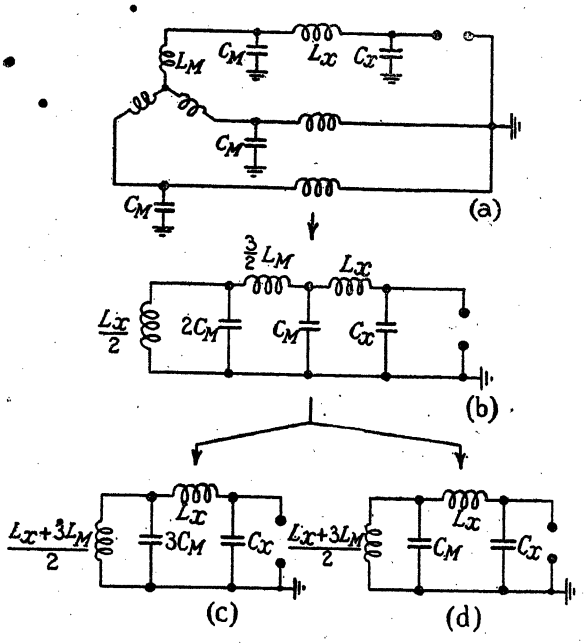
The service conditions discussed cover only the range of current and voltage for which air-blast breakers are likely to be used, and these are, in effect, covered by B.S. 116, Parts I and II, for the corresponding oil circuit-breakers.

The services for which circuit-breakers are used can be classified as follows: (*a*) switching generators, (*b*) switching transformers, (*c*) switching feeders, and (*d*) switching reactors. The majority of h.v. circuit-breakers perform duties (*b*) and (*c*). There are also a number of minor uses which usually only arise with the smaller ratings; these include switching duties for capacitors and motors. In certain instances, these can be brought under one of the above main classifications.

The importance of ensuring that a breaker can cope with all the likely conditions at its location is obvious, but before assessing the probable severities for the various services classified above, it is desirable to consider the types of circuit and the various pieces of apparatus constituting the power system.

(6.1.1) Generators.

Defining generators by kVA rating and percentage reactance



(1) General case (c): $L_x \geqslant L_M$

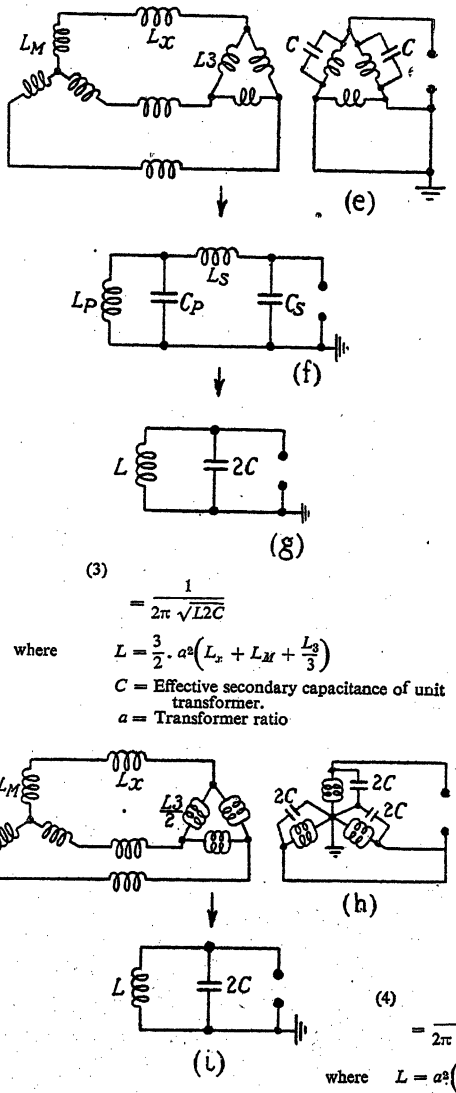
$$f_h = \frac{1}{2\pi}\frac{1}{\sqrt{L_x C_x}}. \qquad \%f_h = \frac{100L_x}{\frac{3}{2}(L_x + L_M)}$$

$$f_l = \frac{1}{2\pi}\frac{\sqrt{2}}{\sqrt{(L_x + 3L_M)3C_M}}. \qquad \%f_l = 100 - \%f_h$$

(2) Special case (d): $L_x < L_M$

$$f_h = \frac{1}{2\pi}\frac{1}{\sqrt{L_x C_x}}. \qquad \%f_h = \frac{100L_x}{\frac{3}{2}(L_x + L_M)}$$

$$f_l = \frac{1}{2\pi}\frac{\sqrt{2}}{\sqrt{(L_x + 3L_M)C_M}}. \qquad \%f = 100 - \%f$$



(3)

$$= \frac{1}{2\pi\sqrt{L2C}}$$

where $L = \frac{3}{2}\cdot a^2\left(L_x + L_M + \frac{L_3}{3}\right)$

C = Effective secondary capacitance of unit transformer.
a = Transformer ratio

(4)

$$= \frac{1}{2\pi\sqrt{L2C}}$$

where $L = a^2\left(L_M + L_x + \frac{L_3}{6}\right)$

C = Effective secondary capacitance
a = Transformer ratio

Fig. 7.—Typical testing station circuits for generators and transformers.

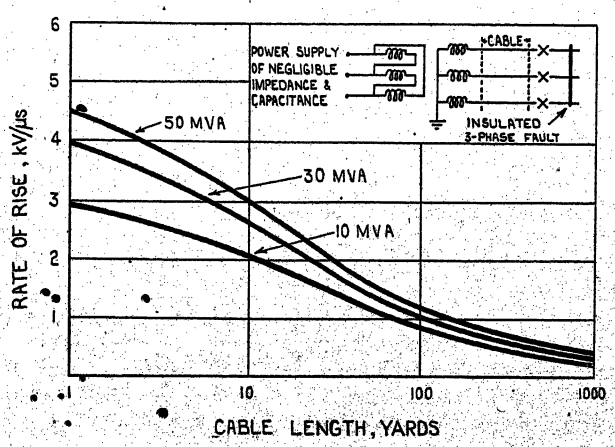


Fig. 8.—Effect of cable length on the rate of rise of restriking voltage for 33-kV transformers.

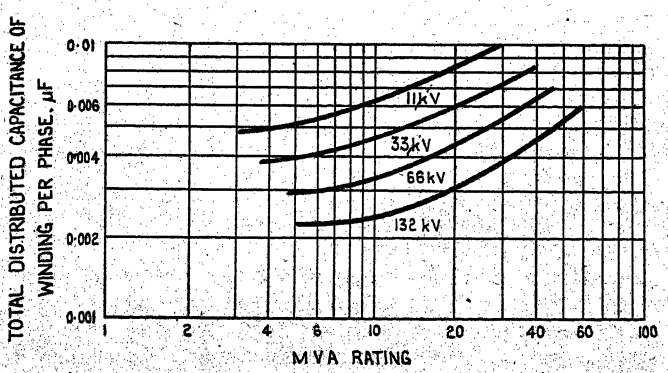


Fig. 9.—Approximate capacitance values for typical core-type transformers.

automatically infers a given inductance value which, while varying with the relative amount of fault current supplied by the generator, is a minimum at the full fault current. Hence the maximum severity in respect to the R.R.R.V. will be found from a consideration of its normal inductance.

The other main component controlling the natural frequency is the effective capacitance of the generator, and the supplementary capacitance of the leads between the generator and the switchgear. This combination can be resolved into the circuit shown in Fig. 7(*a*), assuming L_x is negligible.

The modern practice in h.v. switching is to connect the generators to transformer banks without the intermediary of switchgear, so that the duty on the switch controlling this combination becomes, in effect, that of a transformer switch, the capacitance controlling the oscillation being that of the transformer secondary winding to earth in conjunction with the inductance of the combination.

This is dealt with broadly in the next Sub-section.

(6.1.2) **Transformers.**

The capacitance of transformers is smaller than that of generators, and hence if the reactance of the transformer alone is taken into account a very high natural frequency will be found. In practice, the transformer cannot feed any fault current unless it is in turn fed from another source; consequently the reactance of this source automatically increases the effective inductance, giving a resultant lower equivalent natural frequency with a corresponding reduction in the R.R.R.V.

The upper curve of Fig. 2(*a*) shows a typical restriking-voltage transient of a transformer taken with the restriking-voltage indicator. From the analysis of a number of these records, and from other published data,[9, 10] Fig. 9 has been prepared to show the distributed capacitance for a range of transformers. It will be noted that these capacitances vary with the voltage and kVA rating of the transformer; and variations for the same voltage and rating arise according to type and specification. As the natural frequency varies inversely as the square root of the capacitance, any error in the latter only results in the natural frequency deviating by approximately half the error.

Typical circuit connections for transformer banks are given in Fig. 7(*e*) and (*h*).

(6.1.3) **Feeders.**

In relation to generating and transforming plant, feeders contribute a much heavier capacitive effect with a correspondingly lower reactance, and where feeders are short the capacitance acts as a shunt to the inductive apparatus, reducing the rate of rise accordingly (Fig. 8). For example, a power station built up with a number of reactive components contributing fault current has, in itself, a higher rate of rise when no cables are connected, but as soon as a single cable is connected a considerable reduction results; progressive reductions take place as other cables are connected.

Cables have a greater influence than overhead lines, although the latter have an appreciable effect, especially at higher voltages. As the length of an individual feeder increases it progressively takes over control of the rate of rise until its characteristics completely predominate.

(6.1.4) **Reactors.**

Reactors in themselves, used without knowledge of their transient characteristics, are the greatest potential source of high rates of rise, in view of the relatively small capacitance inherent in the designs. Short cable lengths can however effect an appreciable reduction, and in view of the relatively small numbers of breakers controlling reactors, it seems preferable to lay down a technique of installing them so that their rates of rise do not exceed those of an equivalent transformer.

If this is not done, all the extremely high R.R.R.V. values that could be produced by the use of reactors would have to be explored and their highest values taken, under what in many cases would be freak conditions. The conditions of severity would be such that in many cases the breaker would prove uneconomical.

The natural frequency of the reactors can be reduced by utilizing cables or auxiliary capacitors, or alternatively the reactors could be shunted by resistors. The calculations necessary are given in Section 11.2.5.

(6.1.5) **Grouping of Service Conditions.**

A circuit-breaker to be universal in application must be able to deal with all the conditions of severity which may arise within its MVA rating.

Normal British practice has been to plan networks without reactors as far as possible, while at the same time providing adequate alternative feeds without undue concentrations of power. In certain power stations reactors have had to be used, but the general practice for substations is to have two or three feeders with step-down transformers only. The main stations on interconnected systems supply only part of the total fault currents at the busbars, the remainder being supplied by the feeds from the rest of the network.

Where all the fault power is supplied by local generators either with or without transformers, the highest R.R.R.V.'s are obtained up to the maximum fault-current values. Very few examples of this occur in this country.

To present a picture embracing all the conditions to be satisfied by any breaker, diagrams have been prepared for the various standard voltages and MVA ratings on the basis shown in Fig. 10(*a*) for 132-kV service duties.

Curve A is the R.R.R.V./MVA characteristic that would be obtained with increasing sizes of transformer plotted against their fault MVA, ignoring the reactance of the power feed and assuming the transformers are 10% reactance units as used on the Grid.

Curve B is the R.R.R.V./MVA characteristic for increasing sizes of transformer taking account of the power on the remote side, assuming the feed is $1{\cdot}5 \times 10^6$ kVA.

Curve C is the R.R.R.V./MVA characteristic of two transformers in parallel assuming the same power feed on the remote side. It will be seen that adding another transformer with this feed has the effect of increasing the MVA and at the same time of reducing the R.R.R.V.

Curve D is the R.R.R.V./MVA characteristic of a long overhead line assuming that increasing fault current is fed through it or plant connected to it giving increased fault MVA.

Curve E represents the same conditions for two feeders in parallel.

Curve F is a similar curve for three feeders in parallel.

Figs. 10 (*b*) to (*f*) show the corresponding curves for various voltages from 110 kV to 11 kV.

As proposed previously (Section 6.1.4) the assumption is made that the reactor conditions are adjusted to be equivalent to the transformer conditions, so that the transformer Curve B can in each case be taken as representing the maximum R.R.R.V. due to any reactor.

The transformer curves really represent extreme conditions as a $1{\cdot}5 \times 10^6$ fault kVA feed is assumed. In practice the R.R.R.V. will be lower than this, depending upon the reactance of the circuit on the remote side. Also, any cabling or possible capacitance will further reduce the R.R.R.V.

It will be noted that the curves for the various voltages are drawn on the assumption that the power feed from the local

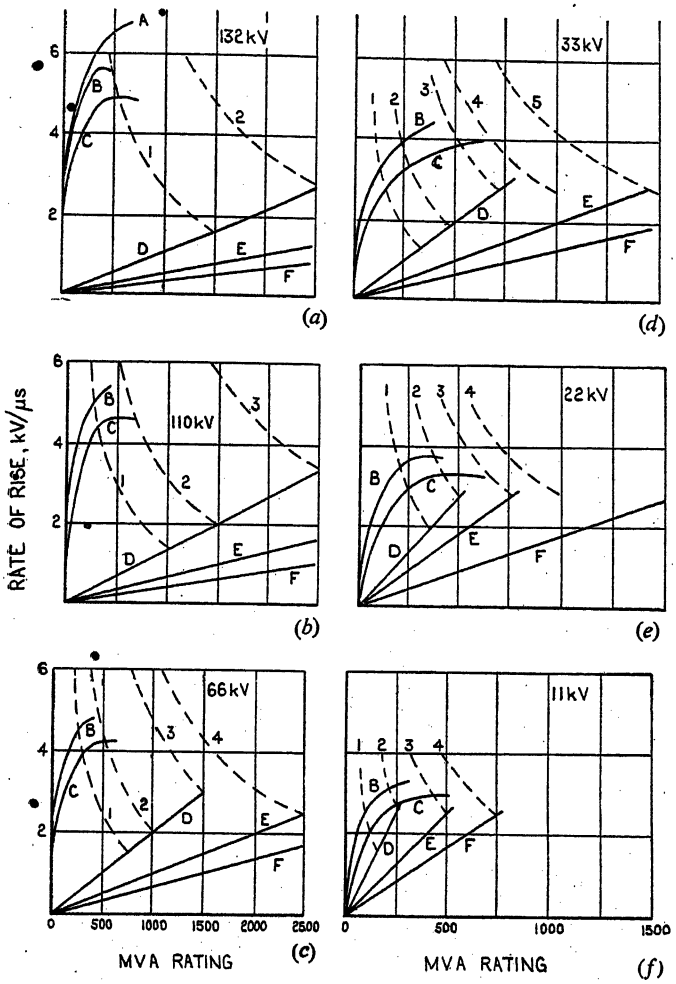


Fig. 10.—Diagrams showing comparison of system severities and breaker characteristics of air-blast circuit-breakers. Curves B to F—Probable maximum system rates of rise in kV/μs. Curves 1, 2, 3, etc.—Proposed minimum characteristics of air-blast circuit-breakers for specific MVA rating.

plant is limited, and that the balance of the fault current making up the total fault MVA at the location is brought in by overhead lines. If cables were substituted for these overhead lines, the rate of rise would be further reduced as the surge impedance of cables is about 1/6 to 1/10 that of overhead lines.

If these curves are considered in relation to the R.R.R.V./MVA characteristics of possible air-blast breakers (Curves 1, 2, 3, 4 in Fig. 10), it will be seen that the switching duty at any location due to transformers on the one hand, and possible feeds from other stations via the overhead lines on the other, will have a somewhat similar shape, since in the average station the transformers can only contribute a percentage of the MVA giving severe rates of rise, whilst with the feeders connected the rates of rise are lower for the heavier MVA values.

(6.2) Testing Stations

The important difference between the testing-station circuits and the conditions outlined above is the concentrated layout of the various components. This enables restriking-voltage transients to be obtained which are generally in excess of system values; yet, owing to difficulties in the physical layout of stations lower restriking-transient values may be obtained at the lower currents. As already shown, this is not a serious matter with oil-breakers, but with air-blast breakers it may have to be considered.

Testing authorities usually have a very complete knowledge of those circuits which permit an equivalent circuit to be readily resolved into one of the recognized standard forms of Section 2.2.

The testing requirements with air-blast circuit-breakers are

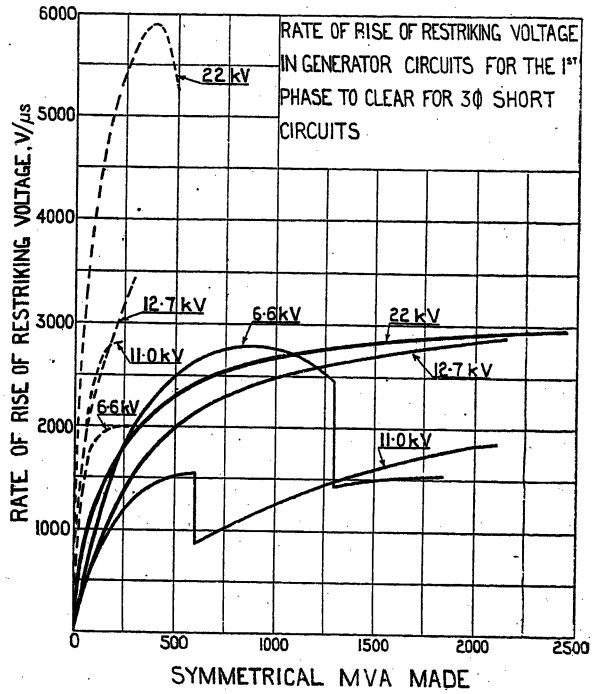


Fig. 11A.—Typical testing station rate-of-rise characteristics. Generator circuits.

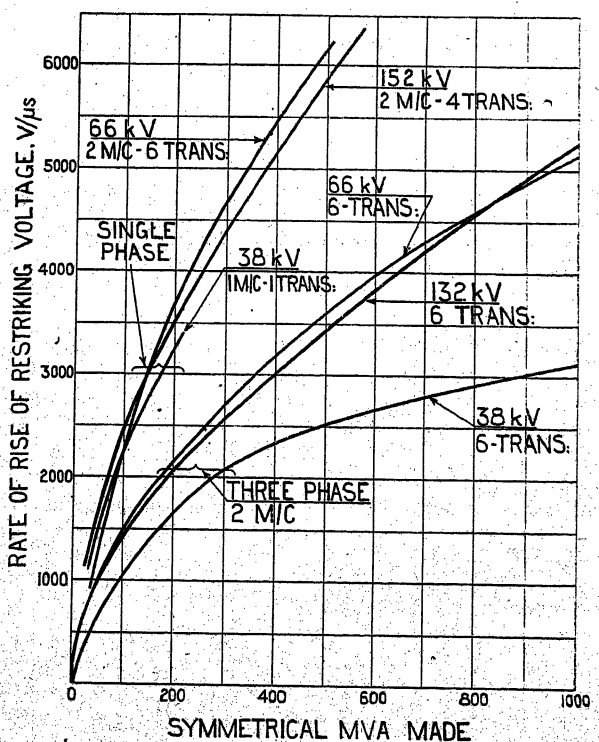


Fig. 11B.—Typical testing station rate-of-rise characteristics. Transformer circuits.

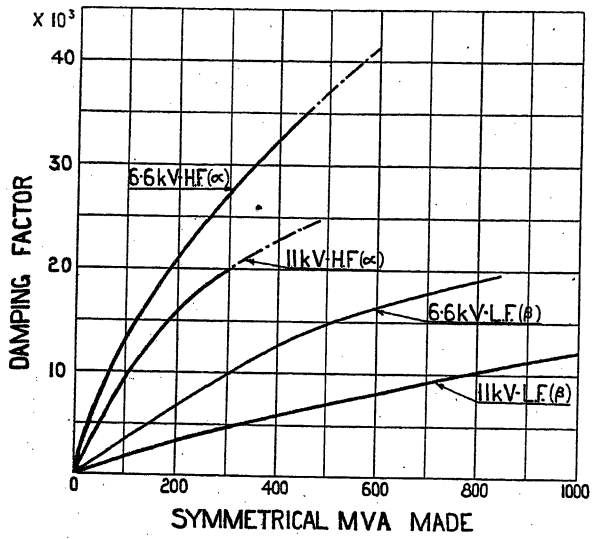


Fig. 11C.—Typical testing station rate-of-rise characteristics. Generator-circuit frequency-damping factors.

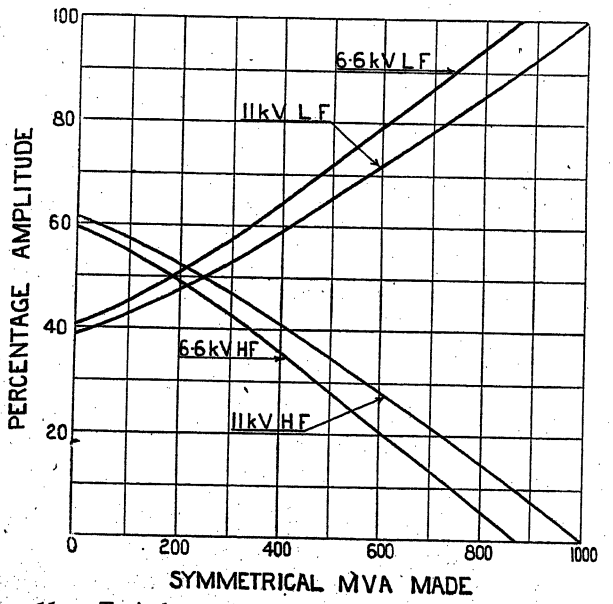


Fig. 11D.—Typical testing station rate-of-rise characteristics. Generator-circuit frequency component amplitudes.

such that before planning a programme of short-circuit tests the inherent transient conditions likely to be experienced must be known, and provision made for an accurate prediction of the short-circuit current and recovery voltage. The methods of calculation are given in more detail in Section 11.1. The rates of rise of restriking voltage at the various test voltages are given for a typical testing station in Figs. 11A and 11B, and typical transients arising from these connections are reproduced in Fig. 2.

(7) PROPOSALS FOR THE STANDARDIZATION OF AIR-BLAST CIRCUIT-BREAKERS

It is evident that an international review of standardization of the air-blast breaker taking cognizance of the rate of rise is called for, and the following proposals are made with the object of establishing a basis for standardization and rating satisfying normal service requirements. Any method of rating adopted must ensure that the R.R.R.V./MVA characteristics of the breaker are adequate to meet the probable maximum service severities.

Consideration of the system-severity curves of Fig. 10 indicates that, generally, the higher rates of rise associated with transformer or other inductive feeds exist over a limited range of fault MVA; whereas rates of rise for MVA values above this range are controlled by the feeders, the effect of the feeders is not so pronounced at the lower voltages as shown in (*e*) and (*f*).

(7.1) Rating

The authors propose to rate the air-blast circuit-breaker in terms of breaking current or MVA broken at a rated voltage and at a rate of rise of restriking voltage. The latter factor would be stated as the maximum system severity that the breaker could deal with when breaking a fault MVA equal to its rating, and for breakers without resistors would imply that a definite R.R.R.V./MVA characteristic approximating to a rectangular hyperbola existed.

The potentialities of this proposal are apparent from an inspection of Fig. 10, where certain possible breaker characteristics are given for comparison with the transformer and feeder severity curves. Thus, if the 132-kV severity curves are considered in relation to the 132-kV, 1 500-MVA R.R.R.V./MVA breaker characteristic (1), it is seen that, provided the fault magnitude contributed by the transformers is not greater than 500 MVA, all possible system conditions can be met by this characteristic. Should a higher rating be required, e.g. 2 500 MVA, this would be more than satisfied by the breaker characteristic (2), the requirements for which are entirely controlled by the feeder severity.

Once it is established that the rating of air-blast breakers can only be given in association with the rate of rise of restriking voltage, the question arises as to what should be the standardized value. It is proposed to assign a rate of rise at the MVA rating greater, by a suitable margin, than the rate of rise of restriking-voltage severity produced by a long feeder when passing a fault MVA equal to the rated MVA of the breaker, this value being modified only where the fault magnitude is possible with a number of parallel feeders. For lower-voltage higher-rated breakers the assessment would be on the basis of three feeders, as the fault MVA can only be obtained by such means.

The breaker characteristics in Fig. 10 were prepared on this basis, where the lowest rate of rise on each characteristic represents the minimum possible R.R.R.V. that could be given to the rating to satisfy all service conditions.

Where breakers employing resistors are being rated, it might be inferred that the resistance has been adjusted to damp out any restriking-voltage transients above the R.R.R.V. that the breaker can deal with when not fitted with a resistor. A rate of rise should however still be stated as part of the rating, so that the adequacy of the resistor can be verified by testing with transients whose rates of rise are equal to, or of the same order as, those given to the rating.

The authors have explored mathematically the site conditions at a number of locations for 132, 110, 66, 33, and 11-kV systems, and they consider that the minimum breaker characteristics in Fig. 10 (*a–f*) should meet average industrial needs.

Although the proposed basis of rating is somewhat arbitrary, it is an endeavour to face the situation created by the greater dependence of air-blast breakers on rate of rise, while retaining sound economic designs of switchgear.

(7.2) Testing

The method of rating proposed, with its reliance for selection on a knowledge of the breaker R.R.R.V./MVA characteristic, makes it necessary to establish the validity of this characteristic.

All breakers should be tested at least over the current ranges laid down in B.S. 116 to prove the satisfactory operation of the contacts, etc. Further type tests should be made to include interrupting transformer-magnetizing currents and capacitance currents, to ensure that the contact adjustments do not allow the breaker to produce voltage rises in excess of those that the system can safely withstand.

During the tests covered by B.S. 116, the test voltages and test circuits should be adjusted to bring their R.R.R.V. characteristics at the higher test MVA's to values just above those obtained from the R.R.R.V. characteristic appropriate to the MVA rating. For lower-voltage heavy-MVA breakers it is very probable that resistance switching must be adopted; hence the testing station should test with the full recovery voltage over as broad a current range as possible up to the rated current, in order to prove that the switching-in of the resistance is satisfactory and that it provides adequate damping.

For breakers whose breaking current rating is in excess of that at which the testing station could give full recovery voltage, i.e. breakers falling under B.S. 116, Part II, the breaker can be tested only in accordance with Part II with as high a recovery voltage and rate of rise as possible. There are, however, certain artifices possible under particular conditions which overcome this serious limitation and give better tests, but due to their dependence on design the details for such tests must be developed according to individual circumstances. For example, the design of h.v. breakers may be such that the breaking device is divided into several series-connected units, permitting a portion of the breaker to be tested at a reduced voltage appropriate to the modified arrangement, and thereby enabling the current range of the test to be extended.

Circuit-breakers built up of several units are the 132, 110 and 88-kV types and probably certain ratings of 66 kV; proposals for testing these breakers are given in detail in Section 11.3.

(7.3) Selection

If the above scheme is adopted, the selection of circuit-breakers will be relatively simple, especially for average substation conditions, which are typical of the majority of circuit-breaker locations. A breaker with a suitable rating can be selected in the usual way provided the fault MVA of the transformer feed is not in excess of that indicated by the breaker characteristic for the transformer rate-of-rise condition; on condition that the other feeds making up the total fault MVA at the location are through cables or overhead lines, the breaker can be installed without any fear of higher rates of rise arising. For example, if the 132-kV, 1 500-MVA case in Fig. 10(*a*) is reviewed, it will be seen that this breaker can deal with up to 500 MVA fed through transformers.

If the fault MVA fed through the transformers is in excess of that indicated by the breaker characteristic for the transformer rate of rise, the rate of rise can be calculated taking account of the reactance of the feed on the remote side of the transformer, the transformer reactance and capacitance, and the capacitance of the interconnecting leads, from which the resultant rate of rise can be checked with the characteristic curve of the breaker. If the rate of rise for the fault MVA is still in excess of the breaker R.R.R.V./MVA characteristic, either capacitance can be added or a breaker of higher rating and a suitable characteristic selected.

(8) CONCLUSIONS

The conclusions arrived at in the paper may be summarized as follows:—

(1) Plain-break oil circuit-breakers and oil circuit-breakers with arc-control contacts are relatively unaffected by the rate of rise of restriking voltage; hence the specification of its value for rating, testing, or selection is not essential, provided the circuit-breakers are tested at testing stations in accordance with B.S. 116 under the severity conditions of the Association of Switchgear Testing Authorities. Such tests ensure that these types of circuit-breakers are suitable for any conditions of service.

(2) The characteristics of air-blast circuit-breakers make it essential to take account of the rate of rise of restriking voltage when rating, testing, and selecting, and in consequence they must be rated in terms of MVA (or breaking current) at a rated voltage and at a rate of rise of restriking voltage.

(3) The authors propose methods for specifying minimum rates-of-rise of restriking voltage for each MVA rating and voltage. The adoption of these proposals enables an economic range of switchgear to be designed that will meet all average conditions of severity in service, and permit economic selection of circuit-breakers to be made.

(4) A simple method of checking the suitability of any breaker rated as above for normal conditions of service is given, together with data for checking the suitability of any breaker for more unusual conditions of service. This method of selection involves calculating the fault MVA in the usual manner and checking that the proportion of the fault MVA contributed locally by generators, transformers, and the like, is not in excess of an amount appropriate to the rating of the circuit-breaker.

(5) Circuit-breakers rated in the manner advocated, i.e. for average service conditions, can also be selected for more severe, but less normal, conditions by adopting the methods described for reducing circuit severity in service.

(6) Proposals are made for testing air-blast circuit-breakers, including synthetic tests for certain types of h.v. circuit-breakers whose MVA ratings are in excess of testing station outputs.

(9) ACKNOWLEDGMENTS

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(11) APPENDICES

(11.1) Short-Circuit Testing-Station Severities

Testing stations are planned to enable the widest possible range of equipment to be tested. The power installation com-

prises generators, transformers, reactors, and resistors. In one typical testing station, the motor generators have a total output of 2 000 MVA based on the symmetrical fault current in the first half-cycle of short-circuit and the rated voltage. When used with the transformer banks the maximum output is reduced to 1 000 MVA on the same basis.

The rates of rise on 3-phase tests are assessed on the basis of the first phase to clear. Where single-phase tests are carried out on single-pole units of 3-phase breakers the recovery voltage (and hence the rate of rise) is adjusted to be equal to that of the first phase to clear for 3-phase tests.

(11.1.1) **Generator Circuits.**

The generator circuits can be connected for 6·35, 11, 12·7 and 22 kV and when used with reactors can be resolved into the phase inductances and capacitances shown in Fig. 7(*a*) for the first phase to clear. In Fig. 7(*a*), L_M is the generator inductance, C_M the generator capacitance between generators and reactors, L_x the control inductance, and C_x the capacitance of the connections. In practice L_x can vary up to about 200 L_M and C_x from about 1/20 to 1/10 C_M, depending on reactance and the circuit-breaker under test.

For the machine in question L_M is about 0·00038 henry at 11 kV on dead short-circuit, and the effective capacitance of each machine phase to ground is 0·05 μF.

Analysis indicates that a circuit as shown in Fig. 7(*a*) produces two natural frequencies; for purposes of calculation this circuit can be simplified to Fig. 7(*b*), which in its turn can be resolved into the circuit of Fig. 7(*c*). The natural frequencies f_h, f_l, produced by such a circuit, together with the percentage voltage associated with each frequency component are given for the general case in Fig. 7(1) where L_x is equal to or greater than L_M, and for the special case in Fig. 7(2) where L_x is less than L_M. The equations for the latter are used for a dead short-circuit on the machine, where $L_x = 0$.

The frequencies are obtained either from short-circuit tests or with the B.T.H. restriking-voltage indicator. With the double frequencies, the percentage voltage associated with each frequency component is proportional to the inductance associated with the respective frequencies in relation to the total inductance. The percentage voltages for the frequencies and the damping factors are given in Fig. 11C and D for two typical generator connections.

The resultant rates of rise determined on the generator connections at various fault MVA values, based on 100% recovery voltage, are given in Fig. 11A. The tangent taken for estimating the rate of rise is that to the first peak exceeding 80% of the recovery voltage peak on the first phase to clear.

(11.1.2) **Tests Using Transformers.**

For higher test voltages the generators are coupled to banks of single-phase transformers giving single-phase or 3-phase circuits for voltages of 33, 66, 76, 114, 132 and 152 kV. The reactance of each transformer referred to the primary is 0·33 ohm at 11 kV and the effective secondary capacitance is 0·0038 μF.

In practice the transient in most cases is of the single-frequency type. The natural frequency is determined by the resultant of the transformer and machine-circuit inductances referred to the transformer secondary, which oscillates with the capacitance of the latter.*

A typical connection for a 3-phase test using the transformer bank is given in Fig. 7(*e*), where L_M is the generator reactance, L_x the added inductance, L_3 the inductance per transformer referred to the primary winding, and C the effective secondary capacitance of a single transformer. Circuit 7(*e*) can be resolved into 7(*f*) which simplifies into 7(*g*). The calculations necessary for determining (*f*) are given in Fig. 7(3).

Fig. 7(*h*) represents a connection with two transformers, in parallel per phase, resolving into circuit Fig. 7(*i*) for which the effective inductance and capacitance used in the frequency calculation are given in Fig. 7(4). The circuits for other connections can be resolved into similar types, and the necessary calculations are easily made.

The resultant rates of rise for the various fault values and voltage connections are given in Fig. 11B.

(11.2) **Calculations of Circuit Severity for Service Conditions**

The rate-of-rise severity for any circuit-breaker location in service can be obtained by application of the following principles and formulae. The calculations give the rate of rise in V/μs (R.R.R.V.) on the first phase to clear in accordance with the other data. The results must of necessity be approximate, being dependent upon the accuracy of the data used, but in general the true values will be rather lower and the results will hence be on the safe side.

Fig. 12 represents a typical substation on which two types of fault are shown.

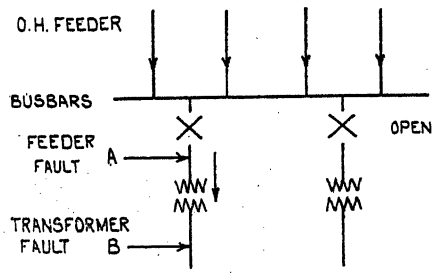


Fig. 12.—Typical substation layout.

(11.2.1) **Locations Where the Rate of Rise is Controlled by Long Lines.**

For this condition a long line consisting of 8 or more miles of overhead lines or 4 miles of cable is used, the fault being taken as fault A in Fig. 12. The fault current may be fed through the lines or from a local supply with the lines merely floating.

$$\text{R.R.R.V. for single long line in V/}\mu\text{s} = 1{\cdot}5Z\left(\frac{di}{dt}\right)_{i=0} \times 10^{-6}$$

where 1·5 is the factor for the first phase to clear,

Z is the surge impedance per phase of the line as obtained from $Z = \sqrt{(L/C)}$, where L is inductance per unit length and C is the capacitance per unit length, and

$\left(\frac{di}{dt}\right)_{i=0}$ is the slope of the fault current as it passes through a normal zero expressed in amp/s, obtained from $\left(\frac{di}{dt}\right)_{i=0} = 2\pi 50 \times \sqrt{2} \times I_{rms}$, I_{rms} being the fault current.[7]

Where more than one line or cable feed is connected to the fault, Z can be obtained from $Z = (1/n)(\sqrt{L/C})$, where n is the number of lines or cables connected to the busbar or feed in question.

(11.2.2) **Locations where the Rate of Rise is Controlled by a Transformer.**

As pointed out in Section 11.1, the reactance to be taken in any calculations involving transformers must usually include the reactance at the remote side, and the capacitance must be taken as that of the transformer winding adjacent to the breaker.

* For a more exact analysis see Reference No. (6).

Two methods can be employed; the method given in Section 11.1 is applicable where large transformers pass a considerable proportion of the total available MVA, while the following method may be used where the MVA passed under short-circuit is restricted to a small proportion of the total MVA available. This condition is represented in Fig. 12 by fault B, the two components of restriking-voltage transient being: (1) that due to the overhead line which, in many cases, can be neglected, and (2) that due to the transformer itself.

The transient frequency of the transformer is obtained from the 50-c/s value of the leakage inductance and the lumped capacitance of the winding and connections adjacent to the circuit-breaker. Fig. 9 gives typical values of the total distributed capacitance for various sizes of transformers, and on the assumption that the transformer neutral is earthed the lumped capacitance value can be taken as about 0·5 of the values given.

The rate of rise of recovery voltage for the transformer taken by itself is

$$4{\cdot}55 \times K \times E^1 \times f \text{ V}/\mu\text{s},$$

where 4·55 is the geometric conversion constant,
K is the oscillation decrement (normally 0·9 to 0·95),
E^1 is the 50-c/s peak recovery voltage (in kV) associated with the transformer:

$$E^1 = 1{\cdot}5L(di/dt)_{i=0} \times 10^{-3}$$

where L is the transformer leakage inductance per phase in henrys and $(di/dt)_{i=0}$ is the slope of the fault current as given in Section 11.2.1.

f is the natural frequency of the oscillation in kc/s:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \times 10^{-3}$$

where C is the effective lumped capacitance in farads per phase of the transformer winding and connections adjacent to the breaker.

The full rate of rise is the summation of the rates due to the transformer and the feeder, but with most step-down transformers the latter can be neglected.

With a long cable feed to the transformer where the impedance is a considerable proportion of the transformer impedance, the rate of rise due to the cable can be calculated as in Section 11.2.1, and the component of voltage due to the transformer calculated as above and added.

(11.2.3) **Locations where the Rate of Rise is Controlled by the Characteristics of Generator-Transformer Sets.**

The calculations for these are as shown in Section 11.1.2 and Fig. 7(*e*, *f*, *g*, etc.), with L_x omitted.

(11.2.4) **Locations where the Rate of Rise is Controlled by the Generator Connections.**

The calculations for these are as shown in Section 11.1.1 and Fig. 7(*b*), etc. This is the more severe case, because normally one generator only is earthed in a power station, the remainder operating with insulated neutral.

(11.2.5) **Locations where the Rate of Rise is Controlled by a Reactor.**

The recovery-voltage transient when reactors are used normally consists of two components, a high-frequency component due to the reactor and a lower frequency or non-oscillatory component due to the remainder of the system. Reactors with high values are rarely used in British practice, their reactance being normally comparable with that of the remainder of the system at the station.

$$\text{R.R.R.V. of reactor} = 4{\cdot}55 \times K \times \frac{X_1}{X_1 + X_2} E \times f \text{ V}/\mu\text{s}$$

where X_1 is the reactance of the reactor,
X_2 is the reactance of the remainder of the system,
E is given by $E = 1{\cdot}5 \times 1{\cdot}414 \times$ rated voltage$/\sqrt{3}$,
f is the frequency of oscillation of the reactor in kc/s as given by $f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \times 10^{-3}$, where L is the inductance in henrys of the reactor and C is the effective capacitance in farads per phase on the reactor side of the breaker including that of the reactor.

The remainder of the restriking voltage can be obtained by calculations based on the constants of the circuit contributing to this rate-of-rise component.

Reactors often have high rates of rise, which it is desirable to reduce to a value approximating to that of a transformer passing the same fault MVA by either (*a*) adding capacitance in the form of capacitors or cables, or (*b*) connecting a resistor across the reactor.

The curves B of Fig. 10 fix the maximum desired R.R.R.V. for the particular fault MVA concerned. These allow the minimum capacitance required for method (*a*) to be determined as follows:—

$$C = \frac{10^{-4}(\text{MVA})K'}{12\pi V^2 U^2}$$

where C is the desired minimum lumped capacitance in μF, U is the desired (maximum) R.R.R.V. in V/μs, K' is $4{\cdot}55^2 \times 0{\cdot}95^2 \times V^2 \times 1{\cdot}5^2 \times 2$, and MVA is the short-circuit rating of the reactor.

For method (*b*) where shunting resistances are used, the desired resistance value can be deduced from the critical damping equation: $R_c = \frac{1}{2}\sqrt{(L/C)}$ ohm, where L is the inductance of the reactor, and C is its self-capacitance; this establishes that the shunt resistance value would be about 250 times the 50-c/s reactance of the reactor.

(11.3) Testing of Air-Blast Circuit-Breakers

The testing of air-blast circuit-breakers with ratings in excess of testing-station outputs is more involved than the testing of oil breakers in accordance with B.S. 116, Part II. Research tests carried out on a 4-break model air-blast construction capable of being tested at voltages up to 132-kV, have proved the suitability of series-connected breaker units for high voltages and have helped to establish a proving technique for such arrangements.

The general laws governing performance for a given voltage per break are: (1) the product of current and R.R.R.V. (or MVA × R.R.R.V.) is approximately constant over a limited range for a given design and generally conforms to a hyperbolic R.R.R.V./MVA characteristic as shown in Fig. 6, and (2) the product of current and R.R.R.V. increases in proportion to nozzle pressure and diameter within certain limits.

Changing the voltage per break may entail altering the geometric relationship of nozzles and contacts, and possibly the air pressure, and this will cause a change in the performance limit of current and rate of rise.

The following argument advances a method for proving the performance of multi-break breakers from certain tests, by applying factors obtained from tests carried out on models.

(11.3.1) **Analysis of Research Type Tests.**

A series of type tests on the above 4-break model were made with a fixed nozzle and electrode arrangement using constant air pressure which gave certain limiting performances on 1, 2, and 4 breaks. The recovery voltages per break were kept constant, and the limit of satisfactory performance was based on the maximum current and rate of rise at which the duration of the arc and the observed stresses began to increase or become erratic.

The recovery voltages and rates of rise across the breaks were recorded, and the recovery voltage across the break with the highest percentage recovery voltage was measured. The test values for these limiting conditions are given in Table 1, the nozzles being adjusted for 33 kV per break.

Table 1

No. of breaks	Recovery voltage V	Breaking current I	Circuit natural frequency f	R.R.R.V. U	% voltage across most stressed break x	Performance P_n $(IU10^3)$	Performance ratio
	kV	kA	kc/s	V/μs			
1	27·3	10·9	6·4	900	100	99	1
1						98 mean	1
1	28	6·6	9·4	1 500	100	97	1
2	57·8	5·5	7	2 400	55	132	0·74
4	106	4·6	7·8	4 400	32	203	0·67

In the following analysis:—

I = maximum breaking current (kA).
U = associated R.R.R.V.
V = normal recovery voltage per break.
n = number of breaks.
p = pressure at the orifice, kept constant during the series of tests

According to law (1) above, the limiting performance of a single break can be expressed as: $P_1 = I_1 U_1$ at V.

Similarly, the performance of the double-break assembly can be expressed as: $P_2 = I_2 U_2$ at $2V$, and the performance of a 4-break assembly as: $P_4 = I_4 U_4$ at $4V$.

Analysis of the conditions existing at the break with the highest proportion of the recovery-voltage across it gives the performance per break for 2 and 4 breaks as:—

2-Break: ${}_1P_2 = I_2 U_2 \times x_2/100$, where x_2 is the percentage of the recovery voltage (and R.R.R.V.) across the highest-stressed break.

4-Break: ${}_1P_4 = I_4 U_4 \times x_4/100$, where x_4 is the percentage recovery voltage (and R.R.R.V.) across the highest stressed break.

The ratios of performance for the 2-break and 4-break models with respect to the performance per single break taken by itself are:—

$$\text{Performance ratio for 2-break} = \frac{I_2 U_2 x_2}{100} \Big/ I_1 U_1$$

$$\text{Performance ratio for 4-break} = \frac{I_4 U_4 x_4}{100} \Big/ I_1 U_1$$

The application of this analysis to the tests is embodied in Table 1.

The tests prove that, for progressive stages of cascading, higher voltages can be handled provided the resultant performance for a single-break nozzle arrangement at a given orifice pressure is modified to allow for the voltage distribution in the breaker and account is taken of the performance ratios for the number of breaks.

These performance ratios for other designs or proportions must be obtained by type tests on accurately proportioned models.

Consequent on law (2), some allowance can be made for pressure variation provided the pressure-performance relationship is proved, and the functioning of the breaker in respect of the operation of the contact, the dielectric conditions, and the current chopping, is not affected.

(11.3.2) **Proposed Method of assessing Performance Tests on Breaker.**

If the breaker has the same general proportions as the model used in the initial type tests, the factors obtained from the above analysis can be applied to suitable tests on the full-size breaker as follows:—

Test Series 1: Test the breaker at full recovery voltage at progressive values of current up to the maximum that can be obtained at the testing station when giving this voltage, and record with the cathode-ray oscillograph the highest percentage voltage and R.R.R.V. across any break of the circuit-breaker.

Test Series 2: Test a single break with exactly the same air-flow conditions, and apply progressive increments of current until the full rated current is reached, the recovery voltage being not less than $x\%$ of the maximum, where x is the percentage recovery voltage associated with the highest stressed break.

During these tests, the R.R.R.V. as well as the current broken should be recorded. Where possible, the limiting performance of the single-break should be obtained with this recovery-voltage value so that the margins of performance over that obtained at the rated current can be determined.

The estimated performance of the breaker when tested at its rated current can be obtained from:—

$$\text{Performance } (P_n) = I_r U_1 \times \frac{100}{x} \times \text{performance ratio}$$

where I_r is the rated current, and U_1 the rate of rise across the single-break with rated current flowing. (For the breaker construction investigated by the authors the performance ratio was 0·74 for 2-break and 0·67 for 4-break.)

The maximum R.R.R.V. that can be handled at the rated current from the above assessment would be given by:—

$$U_n = \frac{P_n}{I_r} \text{ V/μs}$$

From these values of U_n and I_r the breaker characteristic can be drawn.

Where the breaker ratings are such that the above cannot be complied with, an approach to the problem can be made by reducing the nozzle diameter to the maximum size susceptible of complete test, maintaining the design otherwise as intended. The maximum performance so obtained can be corrected in accordance with law (2) for the normal nozzle diameter and for air-pressure variations, and the performance so deduced can then be correlated with the breaker characteristic.

[The discussion on this paper will be found on page 495.]

THE INFLUENCE OF RESISTANCE SWITCHING ON THE DESIGN OF HIGH-VOLTAGE AIR-BLAST CIRCUIT-BREAKERS

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SUMMARY

This paper reviews various problems which are met in designing high-voltage air-blast circuit-breakers, and the way in which the application of resistance switching confers another degree of freedom upon the designer in meeting the many conflicting requirements.

It is first of all shown that a circuit-breaker must not only break its rated breaking current but must also limit the value of surge voltage which it causes while it is opening the circuit. This can be brought about by limiting the electric strength of the breaker contact gaps.

An experimental method of determining the electric strength of the nozzles under air-flow conditions is then explained, followed by discussion of the means by which resistance switching enables the designer to control the breaking capacity and the electric strength of the nozzles independently.

A 132-kV breaker designed in conformity with the conclusions reached is described, and the results of a full-scale test set-up are given.

The paper then gives an analysis of the validity of "unit testing" applied to multi-break breakers with resistance switching, as compared with the present two-part testing applied to oil circuit-breakers in accordance with B.S. 116, Part 2.

In conclusion, proposals are made for a series of type-test duties to be applied to air-blast circuit-breakers, in order to prove compliance with their breaking-capacity ratings.

(1) INTRODUCTION

The application of resistance switching to high-breaking-capacity (h.b.c.) air-blast circuit-breakers for service up to 33 kV is now generally understood, and experience on short-circuit test plants has confirmed the advantages of incorporating switching resistors in all such circuit-breakers which have to deal with high-frequency restriking-voltage transients.

In the development of h.b.c. air-blast circuit-breakers for the highest voltages it is not possible to obtain comparative data on full-scale tests, owing to the limited output of present-day test plants. It is therefore of paramount importance that a high-voltage h.b.c. circuit-breaker should be designed on principles determined by full-scale tests on the lower ratings and should meet all requirements shown by theoretical analysis to be necessary, even though they cannot be proved to be necessary by full-scale tests.

A good air-blast circuit-breaker should:—

(*a*) Interrupt its rated breaking-current at rated recovery-voltage with an economical consumption of air.

(*b*) Interrupt any current within its rating, whatever the restriking-voltage severity of the circuit to which it is connected.

(*c*) Limit the voltage of switching surges at arc interruption to safe values, irrespective of the type of circuit to which it is connected.

It is clear that an arrangement which will render the breaker operation practically independent of the natural frequencies of the circuits to which it is connected will constitute a great advance.

This paper is intended to show how all these requirements can be met by high-voltage air-blast circuit-breakers which incorporate resistance switching.

* British Thomson-Houston Co., Ltd.

(2) RESTRIKING-VOLTAGE TRANSIENTS

When oil circuit-breakers or air-blast circuit-breakers interrupt heavy short-circuit currents at high voltage, interruption occurs at or near a current zero, and the circuit voltage appears across the break in a manner chiefly dependent upon the inductance, capacitance and resistance of the circuit, and upon how these constants are distributed. The transient-in-time by which this voltage appears is known as the restriking-voltage transient.

The most severe transients on high-voltage circuits are experienced when breakers adjacent to reactors or on the high-voltage side of step-up transformers clear faults in close proximity to themselves. Here the inductance and capacitance of the circuit can be taken as lumped, the former in the transformer and the latter in the transformer and connections. Provided the series resistance is small and the resistance shunting the breaker approximates to infinity, such a circuit will give a restriking-voltage transient oscillating with a single frequency

$$f = \frac{1}{2\pi\sqrt{(LC)}}$$

where f = natural frequency, in cycles per sec.
L = circuit inductance, in henrys.
C = circuit capacitance, in farads.

Where the inductance and capacitance are shunted by a resistance of value other than infinity,

$$f = \frac{1}{2\pi}\sqrt{\left[\frac{1}{LC} - \left(\frac{1}{2RC}\right)^2\right]}$$

where f, L and C have the same meaning as before and R is the shunt resistance in ohms.

From this formula it will be seen that if R is less than $\frac{1}{2}\sqrt{(L/C)}$ the expression under the root sign becomes negative, which means that the oscillating nature of the transient vanishes and it becomes an exponential transient. Fig. 1 illustrates the three types of transient.

The performance of properly constructed oil circuit-breakers is not greatly influenced by the shape of oscillatory restriking-voltage transients met with in practice, but it is found that the performance of air-blast circuit-breakers which do not incorporate resistance switching is very seriously affected, and great economy in air consumption can be brought about by reducing the frequency of the transient or making it exponential.

It will be seen that the natural frequency of the transient will be reduced by:—

(*a*) Increasing L.
(*b*) Increasing C.
(*c*) Reducing the value of R shunting L and C.

From this it follows that for a given MVA short-circuit rating of a circuit, the higher the circuit voltage the lower becomes the natural frequency of the transient, because not only does the reactance increase as the square of the circuit voltage, but the capacitance also increases, owing to the greater physical size of the apparatus. Conversely, in order to obtain the same natural

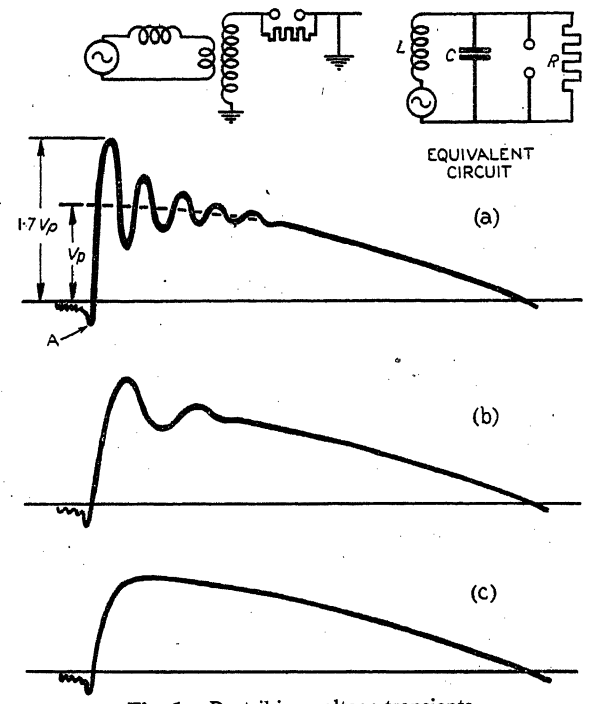


Fig. 1.—Restriking-voltage transients.
(*a*) R approximates to infinity. Damping is due to energy losses in L and C.
(*b*) R is less than infinity but greater than $\frac{1}{2}\sqrt{(L/C)}$. Neglecting energy losses in L and C.
(*c*) R less than $\frac{1}{2}\sqrt{(L/C)}$. Neglecting energy losses in L and C.

frequency the MVA rating of a high-voltage circuit must be considerably greater than that of a low-voltage circuit.

When the voltage and MVA of a circuit are fixed, the transient can be influenced only by increasing C or reducing R. To increase C is uneconomical, but a reduction in R can be brought about by shunting the breaker with a resistance during the switching period. This is known as resistance switching.

In resistance switching the breaker is provided with two breaks, one of which is shunted by a resistor (see Fig. 8). The arc in the shunted break is extinguished first and the resistor then shunts L and C until the arc carrying the resistor current in the second break is extinguished. By this time the restriking-voltage transient has decayed to a negligible value.

When the value of R is made low enough, the restriking transient becomes practically independent of the natural frequency of the circuit on which the breaker is used, and is so reduced in peak value and rate of rise that the size of nozzle forming the shunted break can, for a given breaking capacity, be greatly reduced.

The economies to be attained in nozzle size and air consumption by using resistance switching on h.b.c. air-blast breakers up to 33 kV when used on circuits having high-frequency restriking-voltage transients, are now thoroughly substantiated by full-scale breaking-capacity tests.

Owing to the reduction in natural frequency of a circuit of a given MVA short-circuit rating, the value at which resistance switching becomes advisable on circuits of 132 kV and above, if considered entirely from an air-economy standpoint, is above the full-scale testing capacity of any existing test plants. This means that the need for switching resistance is masked, as all breaking-capacity tests at the full rating are taken at a reduced voltage.

Before adopting the "brute force" method of merely supplying sufficient air to do the job, the value of resistance switching, as conferring another degree of freedom on the designer in controlling switching over-voltages, must be considered.

(3) TYPES OF SWITCHING OVER-VOLTAGES MET WITH IN PRACTICE

Over-voltages generated when opening a circuit can be brought about by many causes, the three most important of which are as follows:—

(*a*) Whenever an inductive circuit is finally broken substantially at the zero of current, the voltage is re-established across the break by the usual restriking-voltage transient, which theoretically rises to double the peak value of the 50-c/s recovery voltage, but usually does not exceed 1·7 times the peak value (V_p) of the 50-c/s recovery voltage [Fig. 1 (*a*)].

(*b*) Very high voltages can be generated when opening capacitance currents such as line charging-currents.*

(*c*) Another class of high-voltage transient is that due to pre-zero current suppression in inductive circuits, known as "current chopping" (see Fig. 2).

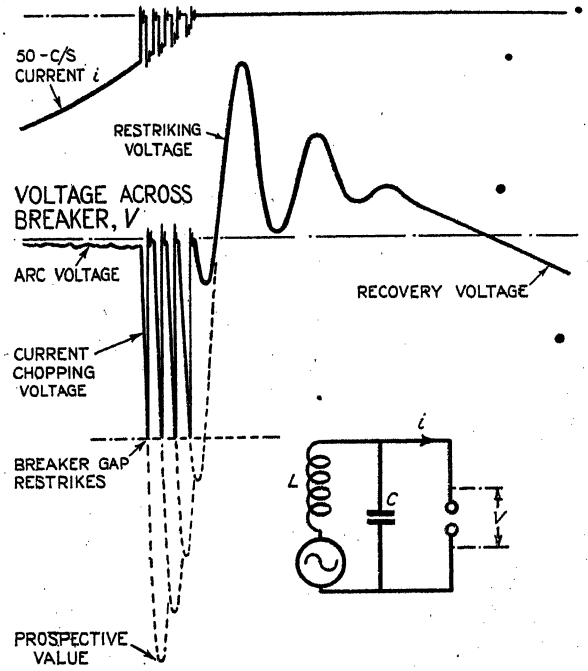


Fig. 2.—Multiple current-chopping in an inductive circuit.

The first type of over-voltage is normal when opening inductive circuits, and must be withstood by the breaker gaps and all parallel insulation paths.

In practice it may often happen that the two other types of over-voltage can rise to very high prospective values and, unless they are limited by some means, will cause external flashover across the breaker insulation or flashover to earth elsewhere on the system. The usual method of limitation is by restrike of the breaker contact gaps.

Current-chopping over-voltages are the easiest to reproduce on test plants, and as a breaker which is designed to deal adequately with and control this type of over-voltage will also deal with any other type of over-voltage, a complete analysis of this case will now be made.

(4) ANALYSIS OF OVER-VOLTAGES CAUSED BY CURRENT CHOPPING IN INDUCTIVE CIRCUITS

As the 50-c/s current being interrupted approaches zero, a value is reached at which de-ionization of the arc in the contact

* HUNT, L. F., BOEHNE, E. W., and PETERSON, H. A.: *Transactions of the American I.E.E.*, 1943, 62, p. 98.

gap is so rapid that the current is forcibly suppressed before the natural zero point. If the total reactance of the circuit is such that the current to be interrupted is of the order of 150 A(r.m.s.) or above, this forcible suppression occurs when the current has nearly reached its normal zero.

The instantaneous value of current chopped is then very small, and the voltage induced in the circuit inductance appears as a small loop in the same direction as the arc voltage, as shown at "A" in Fig. 1(*a*).

With higher values of circuit reactance giving lower values of 50-c/s current, the total amount of ionization of the contact gap is less, and suppression of the current occurs earlier in the half-cycle and thus at a higher instantaneous value, thereby inducing a higher voltage in the increased circuit inductance.

With a correctly designed breaker this voltage is prevented from rising to a dangerous value by breaking down the contact gap and re-establishing the normal arc. The arc current which flows is again forcibly suppressed and the process is repeated until the current almost reaches its normal zero, as shown in Fig. 2.

Fig. 3 shows a cathode-ray oscillogram of a case where multiple current chopping takes place during a full half-cycle of current. An extreme case is that of breaking the magnetizing current of a transformer.

When current is chopped in a circuit comprising inductance and capacitance in parallel, in a time short compared with the natural period of the circuit, the voltage generated becomes independent of the rate of chopping and varies directly as the current chopped. The voltage is

$$V = i\sqrt{\frac{L}{C}}$$

where V = voltage generated (peak), in volts.
i = instantaneous value of current chopped, in amperes.
L = circuit inductance, in henrys.
C = circuit shunt capacitance, in farads.
$\sqrt{\frac{L}{C}}$ = surge impedance, in ohms.

Over the range where these voltages become dangerous this condition of rapid current suppression is met and the prospective value of V amounts to several times the insulation level of standard apparatus.

The suppression of current not only causes voltage to earth but also induces local voltages in individual pieces of inductive apparatus.

As already stated, the usual limitation to the voltages is imposed by restriking of the contact gap or failure of external insulation (see Fig. 2).

Surge divertors as usually connected for lightning protection cannot be considered as a protection against all manifestations of switching over-voltages.

It therefore becomes an essential part of circuit-breaker design to ensure that under all circumstances the electric strength of the contact gap or nozzle is kept as low as possible consistent with withstanding the maximum normal restriking transient when clearance finally occurs at a normal zero.

(5) REQUIREMENTS OF INTERRUPTING NOZZLES FOR USE IN AIR-BLAST CIRCUIT-BREAKERS

A correctly designed nozzle or series of nozzles must meet the following basic requirements:—

(*a*) Must break the rated breaking-current at rated voltage when operating on circuits of any restriking-voltage severity which may occur in service and when supplied with air at the minimum safe operating pressure.

(*b*) Must not permit excessive switching over-voltages when breaking any current within its rating on any type of circuit and when supplied with air at the maximum allowable air pressure.

In determining the best form of nozzle to meet these requirements many arrangements have been investigated for both interrupting ability and electric strength. The performance of most forms was marred by periodical inconsistency of arcing time when interrupting heavy currents. This inconsistency is not only undesirable from the point of view of the finished breaker, but also makes it very difficult to obtain consistent design data with a reasonable number of heavy-capacity short-circuit tests.

Efforts were therefore first directed to developing the form of nozzle which gave the most consistent arcing times when breaking short-circuit currents up to its failure point.

(5.1) Consistency of Arcing Time and Electric Strength

Consistent and short arcing times are best achieved by ensuring that not only is the arc initially drawn in a region of high air velocity, but that all restrikes take place in such a region. This requirement is unfailingly met in the radial-flow double-blast type of nozzle shown in Fig. 4 on which much investigational work has been carried out in Great Britain by the British Electrical and Allied Industries Research Association.

In this type of nozzle the air flows radially inwards, and its velocity is thus increased considerably owing to the reduction in area of the path. This increase of velocity is accompanied by a reduction in pressure (Bernouilli's law), and this in turn results in a reduction of the electric strength (Paschen's law). Provided a correct ratio is chosen for l/d (see Fig. 4), the minimum electric strength can be made to occur at the orifices. Thus the region around the orifices of each electrode is filled with air of reduced electric strength travelling at high speed into the orifices. With this form of nozzle, not only is the arc initiated next to the orifices (by virtue of the camber on the contact surfaces) but each restrike takes place immediately from the peripheries of the orifices (by virtue of the reduced electric strength).

(5.2) Experimental Investigation of Electric Strength and Arc-Centring Properties of Radial-Blast Nozzles

The electric strength and behaviour of this form of nozzle has been studied by the authors by means of timed impulses from an impulse generator, and a pin-hole camera photographing the resultant spark-over.

Restriking of the arc in a circuit-breaker gap can occur by one of two methods:—

(*a*) By V^2/R loss in the resistance of the residual arc column (post-arc conductivity).

(*b*) By arc-over of the completely de-ionized gap by the restriking-voltage transient.

Method (*a*) can be investigated only on a full-scale test plant capable of giving the full rated MVA breaking capacity.

Method (*b*), however, can be investigated with the aid of an impulse generator only. Experiment gives ample evidence to show that, provided the gap passes sufficient air to prevent restrike by method (*a*), the air will have swept all residual ionization from the gap by the time the maximum peak voltage of the restriking transient is reached, so that the gap will be in exactly the same condition as it would have been if no arcing had taken place.

This means that the electric strength found by applying a voltage under air-flow conditions but without any previous arc will be the same as under actual working conditions of breaking rated current.

It is, of course, not convenient to leave air on the nozzles sufficiently long for a steady 50-c/s breakdown voltage to be established, in view of the large quantity of air which would be

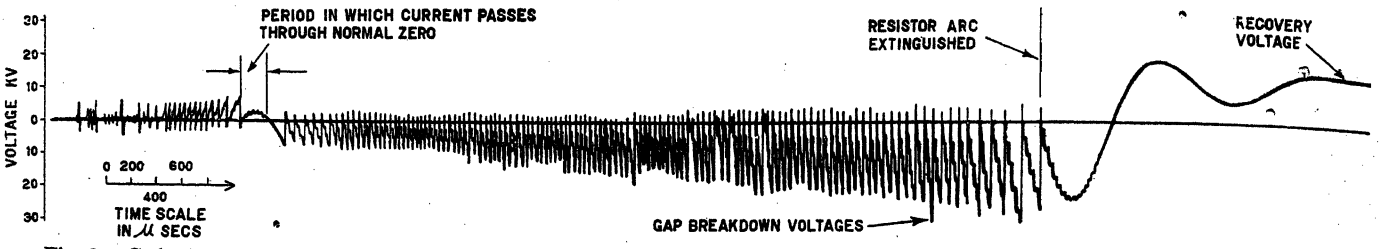


Fig. 3.—Cathode-ray oscillogram, showing multiple current-chopping. Record obtained on an 11-kV air-blast breaker when interrupting 10·2 A at 12 kV recovery voltage (single-phase).

used. This can be overcome by applying impulse voltages. In practice this is brought about by connecting an impulse generator to the gap under test and triggering-off the impulse generator by a pulse of air taken from the breaker blast-head and passing it through a length of pipe. By this means the correct delay is

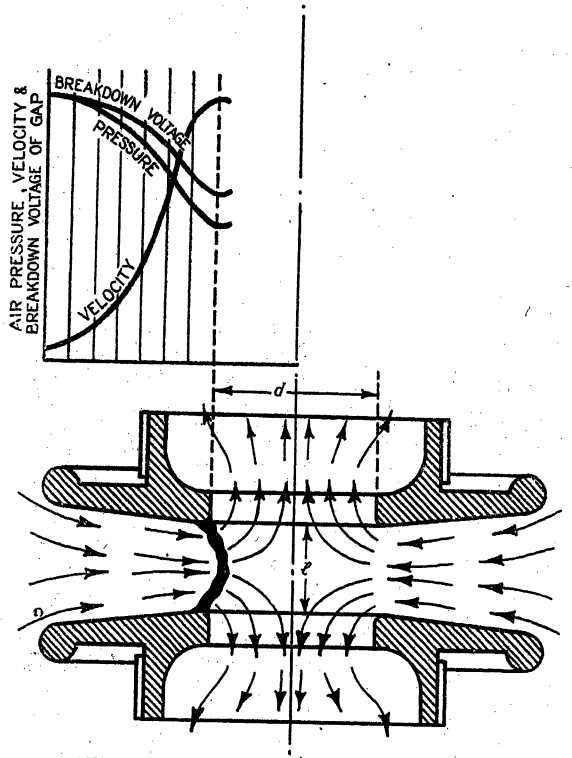


Fig. 4.—Radial-flow double-blast nozzles.

given to ensure that the impulse voltage is applied at exactly the same time as the gap reaches its full-open position and air flow is established. Fig. 5 shows diagrammatically an arrangement of a test set-up to obtain the full-wave flashover voltage. The operation is as follows:—

The impulse generator A is charged from the 50-c/s supply through a rectifier, and a trip impulse is then applied to the air-blast breaker which admits air to the blast head B. Part of the air travels along the delay pipe and closes the air-operated sphere gap on the impulse generator, thus initiating the voltage impulse. By correctly proportioning the length and the volume of the delay pipe, the impulse-voltage transient can be made to appear on the head B just when the contacts are fully open and air flow has been established. The 50-c/s charging voltage corresponding to any required impulse voltage is obtained by calibrating against the sphere gap prior to the tests. During calibration the complete set-up is connected, and calibration is taken by the 50% flashover method at voltages not more than 10% below the required voltage.

(5.3) Results of Electric-Strength Tests

Tests very quickly showed inconsistency in breakdown value between successive tests, although the greatest care was taken to ensure the same conditions of air pressure, timing, etc. This feature has also been observed by workers investigating the

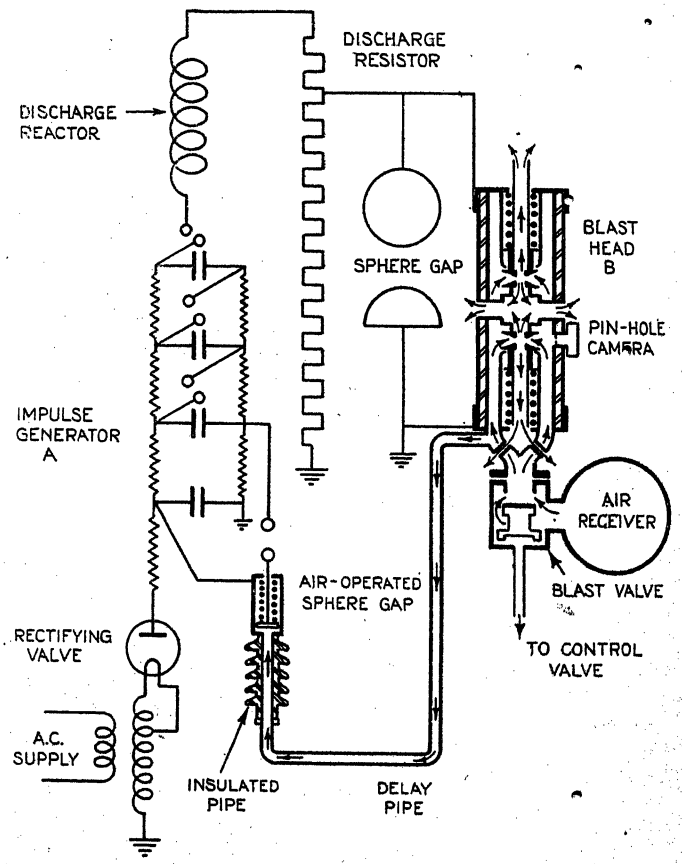


Fig. 5.—Diagrammatic arrangement of test circuit for measuring the electric strength of nozzles under air-flow conditions.

breakdown of air at high pressures under static conditions.* Fig. 6 shows a chart of 51 consecutive tests.

Alternate tests were taken at what was considered to be the maximum "withstand" voltage and the minimum "consistent breakdown" voltage. The maximum "withstand" voltage is the maximum voltage to give no breakdown on at least 10 consecutive full-wave tests at that voltage, and the minimum "consistent breakdown" voltage is the minimum voltage to give breakdown on at least 10 consecutive full-wave tests at that voltage. The spread between these two voltages must be taken into account when designing nozzles for any given duty.

The same experimental method can be used to find the maximum break distance which can be associated with any nozzle

* Howell A. H.: *Transactions of the American I.E.E.*, 1939, 58, p. 193.

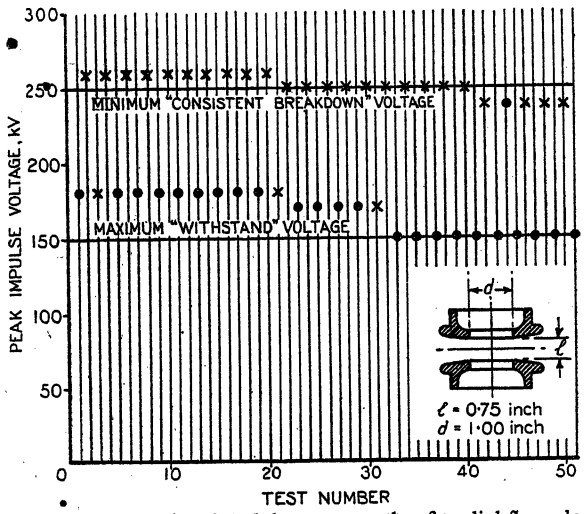


Fig. 6.—Chart showing breakdown strength of radial-flow double-blast nozzles.

× Breakdown. ● No breakdown.

diameter and yet ensure that restrikes always occur from the internal periphery of the orifice. For this purpose a pin-hole camera is placed opposite the orifices and photographs are taken of each sparkover.

Fig. 7(*a*) shows the nozzles as viewed by the pin-hole camera, and Fig. 7(*b*) is a reproduction of an actual photograph. The outline of the orifices is clearly visible, although the exposure was not of sufficient duration to show the outline of the nozzles themselves. The arc roots and the reflections of the arcs across the contact surfaces are clearly visible.

Fig. 7(*b*) shows the arcs resulting from three separate tests; one occurring from the left-hand side of the orifice, one on the near side of the orifice directly in front of the camera, and the third from the right-hand side of the orifice. The movement of the arc and flame in the air stream is clearly visible for the two arcs which occurred at the side of the orifice.

(6) DESIGN OF NOZZLES TO INTERRUPT RATED BREAKING CURRENT AT RATED VOLTAGE

The breaking capacity of any nozzle depends upon the air pressure, the diameter of the orifices, and the frequency of the circuit restriking transient.

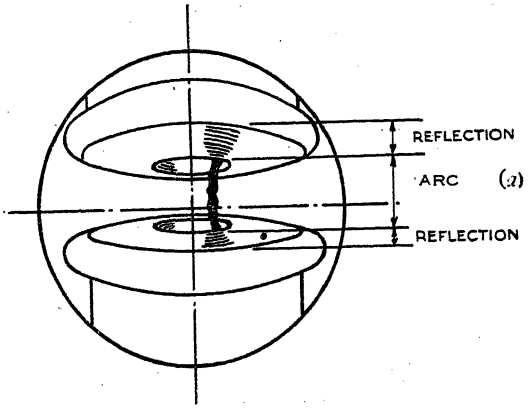
The electric strength of the gap depends upon the break distance and the air pressure. The break distance is, however, definitely related to the orifice diameter in order to ensure correct flow conditions.

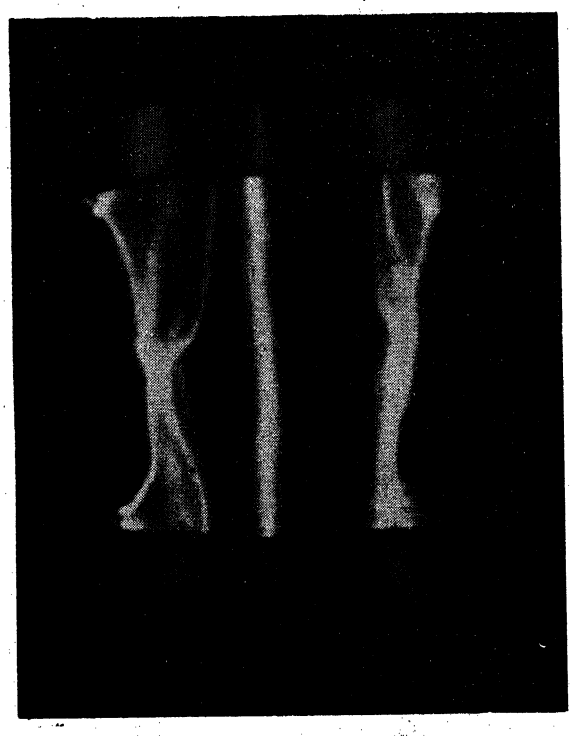
It therefore follows that, unless the restriking transient can be controlled, the breaking capacity required determines the size of orifices (and therefore the gap length) and thus also determines the electric strength of the gap.

Under conditions of maximum circuit severity it is found that the nozzles required for quite moderate breaking capacities have electric strengths considerably in excess of the minimum required to withstand the restriking-voltage transient met with when interruption occurs at a normal current zero. This means that dangerous voltages can be permitted when breaking small inductive currents and capacitive currents.

(7) LIMITATION OF ELECTRIC STRENGTH OF NOZZLES BY USING RESISTANCE SWITCHING

When the breaking-capacity requirements dictate the use of nozzles with too high an electric strength, resistance switching can





(*b*)

Fig. 7.—Photograph of arc-over of nozzles under air-flow conditions.

(*a*) Contact nozzles as seen through pin-hole camera.
(*b*) Photographs of 3 arcs (enlarged approximately 2 diameters).

be introduced to give the designer another degree of freedom. Fig. 8 shows two possible arrangements.

In Fig. 8(*a*) two gaps are placed in series, one being shunted by a switching resistance and both being supplied with compressed air independently of each other. Here both gaps are made to open at approximately the same time. This timing is not critical. Both gaps clear the arc at the first suitable current zero. The resulting restriking transient by-passes gap No. 1 through the resistor and breaks down gap No. 2 with the resistor in series. At the next current-zero gap No. 2 has the comparatively easy duty of breaking the resistor current only, but is subjected to any switching surges which may appear.

In Fig. 8(*b*) gap No. 1 is shunted by a resistor in series with a permanent gap No. 2. Here the air is first fed to gap No. 1 and then passes on to gap No. 2. Immediately after gap No. 1 has ceased to carry current, gap No. 2 is still fed by hot ionized air which causes it to be broken down by the restriking transient, in preference to gap No. 1. At the next current zero, gap No. 2 is

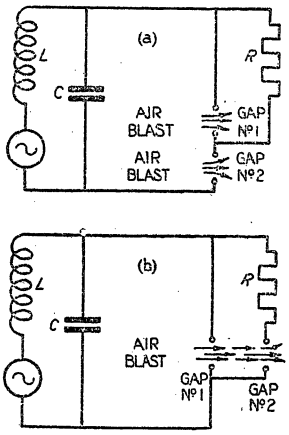


Fig. 8.—Methods of resistance switching.

fed with cold un-ionized air and the resistor current is in turn broken.

It will thus be seen that the voltage transient encountered on finally clearing the circuit is impressed on gap No. 2 only in the case of Fig. 8(*a*); and on gaps 1 and 2 in parallel in the case of Fig. 8(*b*). As, however, gap No. 2 has to clear only the resistor current, it can be made with a minimum electric strength, and thus limit the voltage transient which may appear when breaking capacitive currents, or when current-chopping in inductive circuits occurs.

Under these conditions gap No. 1 can be proportioned solely to clear the rated breaking-capacity current, and no thought need be given to the electric strength which the gap attains.

In practice it is found that arrangement 8(*a*) is most suitable for breakers of 66 kV and above; whilst arrangement 8(*b*) is most suitable for 33 kV and below.

(8) DESCRIPTION OF A 132-kV AIR-BLAST CIRCUIT-BREAKER INCORPORATING RESISTANCE SWITCHING

A circuit-breaker with a rating of 2 500 MVA at 132 kV has been developed on the principles set out in this paper, and the many novel features which have been incorporated in the design can be understood from the following detailed description of its construction and performance.

(8.1) Construction

Fig. 9 shows two views of a single-phase unit of the breaker.

Two double-break blast heads are employed per phase, one of which is shunted by a wire-wound non-inductive resistor.

Each blast head is separately mounted on its own blast valve and air receiver, and is supported, by a post insulator, from a rigid tubular base in which are housed the electro-pneumatic control valves.

Opening and closing of the blast valve are effected through small-bore porcelain tubes which extend from each blast valve to the control valves in the centre of the base. These tubes are also used to charge the air receivers.

The blast heads are coupled at the lower ends by an air-break isolating switch comprising two blades arranged to rotate horizontally and driven through torsion insulators by an air-operated mechanism in the base.

(8.2) Blast Heads

Fig. 10 is a sectional drawing of the shunted blast-head. The two breaks are enclosed in a paper-insulation cylinder. A central exhaust chamber carries the fixed contacts, while the movable contacts, together with their operating pistons, contact

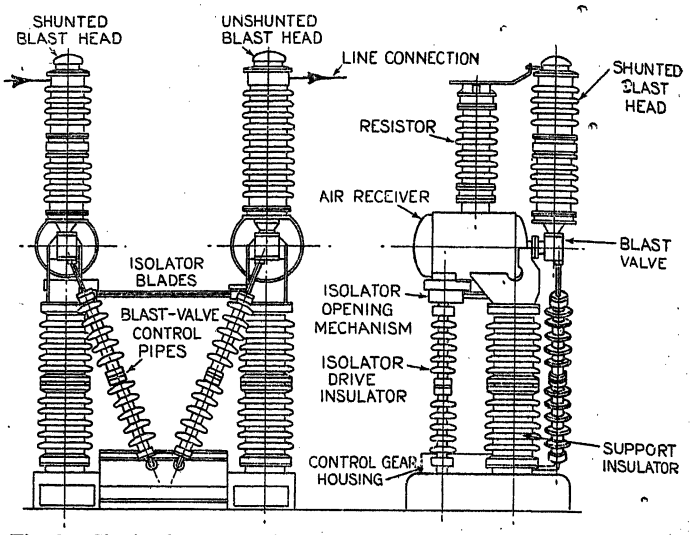


Fig. 9.—Single-phase unit of a 132-kV air-blast breaker incorporating resistance switching.

springs and sliding contacts, are assembled in metal cylinders located from each end of the paper-insulation cylinder.

The blast head is enclosed by two porcelain weather-shields, and the interspace is fed with dry air at a pressure slightly above atmospheric.

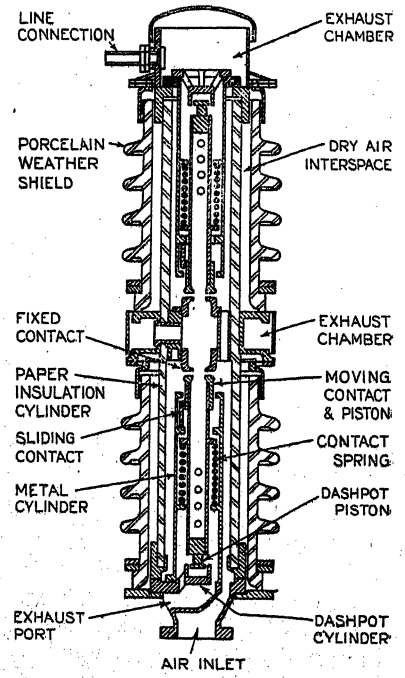


Fig. 10.—Section of shunted blast-head for 132-kV air-blast breaker.

The fixed contacts are mushroom-shaped with a central exhaust hole, and have silver contact rings brazed on, while the moving contacts take the form of hollow pistons with similar silver-faced mushroom heads.

When compressed air is admitted at the lower end of the head it fills the annular space between the moving-contact housings and the paper-insulation cylinder, and the movable contacts of each break are forced away from the fixed contacts against the action of the contact springs. The air then passes through the hollow contacts, thus scavenging the arcs formed between them, and flows axially through the exhaust tubes fixed to the moving

contacts, escaping to atmosphere through ports at each end of the blast head. The air flowing through the fixed contacts is exhausted radially outwards from the middle of the head.

Both blast heads are similar in construction, but each head is proportioned to suit its particular duty. The shunted head has large-diameter nozzles and corresponding length of contact gap to interrupt the rated breaking-current, while the unshunted head has smaller nozzles and shorter contact gaps to interrupt the resistor current. As the maximum voltage which can appear across the shunted head is limited by the resistor and is independent of the electric strength of the gap, the external flashover value of this head is made to suit the 50-c/s recovery voltage of the breaker.

On the other hand the unshunted head has to withstand the maximum restriking-voltage transient, and is therefore longer and has a higher external flashover value.

(8.3) Blast Valves and Control Valves

The blast valves operate on a differential-pressure principle which is shown diagrammatically in Fig. 11.

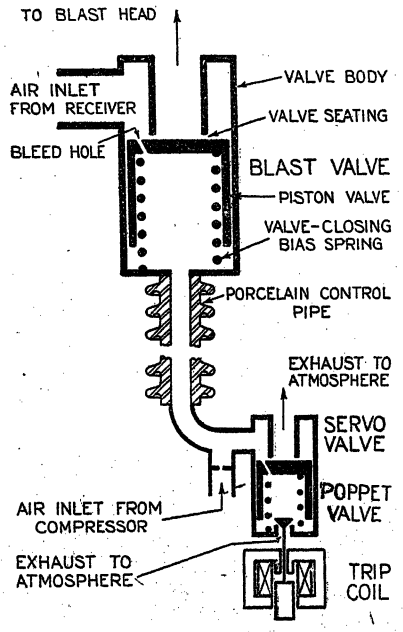


Fig. 11.—Schematic arrangement of blast valve and control valves.

When the valve is closed, the whole of the valve body is filled with compressed air from the air receiver, the volume behind the piston valve being filled through a bleed hole in the piston head. The piston valve is biased towards the closed position by a spring and is held firmly closed by the full air pressure acting on the area enclosed by the seating.

The area of the piston valve is approximately twice the area enclosed by the seating, so that if the volume behind the piston valve is suddenly exhausted to atmosphere, as soon as the pressure falls below half its initial value, the differential pressure on the piston causes the valve to open.

As air escapes past the seating its pressure over the area enclosed by the seating is then added to the opening force and the piston valve opens rapidly.

The main blast valve is exhausted to atmosphere through a servo-valve which is also of the differential type, and the back of its piston valve is exhausted by the opening of a small poppet valve actuated by the trip coil.

(8.4) Switching Resistor

This is built up of a number of pancake coils, adjacent coils being wound in opposite directions.

By an ingenious construction, joints between coils are eliminated and the heavy-gauge nickel-chrome wire is wound in one continuous length.

A spring at one end of the spool allows for axial expansion of the resistor, and the complete assembly of the coils is enclosed in a porcelain weather-shield filled with a non-inflammable cooling medium.

(8.5) Series Isolator

The two isolator blades are pivoted from the air receivers and retract from each other to give a very high effective opening speed with greatly reduced inertia forces compared with a single-blade design.

Synchronous movement of the blades is ensured by mechanically coupling the torsion insulators at the earthed end, and the coupling rod also drives an auxiliary switch to give positive indication of the position of the blades.

The isolator is closed by rotating the torsion insulators by means of an air cylinder in the base, and is then held in the closed position by a powerful spring.

A very high rate of acceleration is obtained on the opening stroke of the isolator by means of an air cylinder coupled to one of the blades. This cylinder is fed directly from the shunted blast-head so that an opening operation cannot be initiated unless the blast valve is open and pressure has built up in the blast head. The opening stroke is completed and the blades are held securely in the open position by the same spring that performs this function in the closed position.

The blades are so arranged that after the butt contacts make on a closing stroke they then slide across one another, giving a self-cleaning action. Before the contacts part on an opening operation, the same sliding action occurs in the reverse direction, thus effectively shearing any accumulation of ice. In the fully open position the ends of the blades are retracted into a housing, fitted with rubber doors, which prevents snow and ice from accumulating on the contact faces.

(8.6) Operating Data

The operating data for the 3-phase breaker are as follows:—

Pressure for proving rated breaking capacity (i.e. lock-out pressure), 200 lb/in^2 gauge.

Normal operating range (minimum), 238 lb/in^2 gauge.

Normal operating range (maximum), 263 lb/in^2 gauge.

Design pressure of receivers, 300 lb/in^2 gauge.

Air consumption on a break test for the 3-phase breaker at 238 lb/in^2 gauge, 130 ft^3 of free air.

(9) PERFORMANCE OF 132-kV AIR-BLAST CIRCUIT-BREAKER

(9.1) Test Results

Table 1 shows a series of 48 break tests ranging from 20 A to over 11 000 A, which latter is the symmetrical breaking-current rating for a 3-phase 132-kV 2 500-MVA breaker. These tests were taken on an experimental model.

A complete series of 35 tests (Nos. 431–465) was carried out in uninterrupted sequence except for an examination of the contacts which was made after test 445.

Further tests taken subsequently to the above series have been inserted in the Table to show the performance at the highest and lowest breaking currents obtainable.

The test circuits were arranged to give recovery voltages of approximately 132, 114, 76, 60 and 40 kV, and the breaking

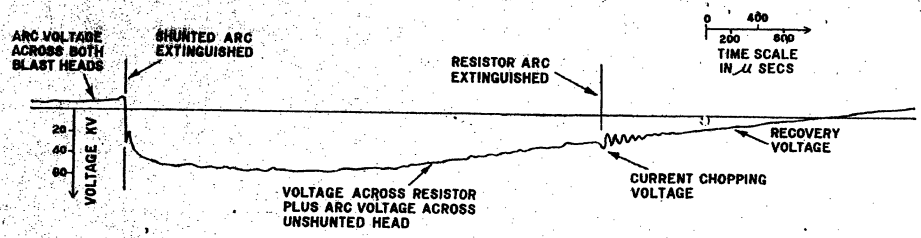
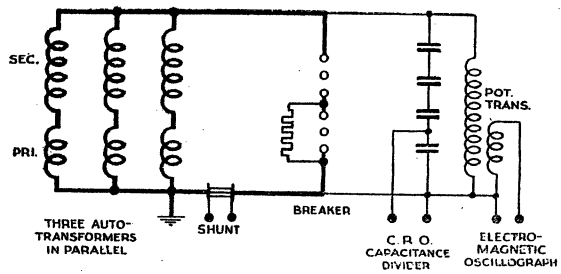


Fig. 12.—Cathode-ray oscillogram of Test 464 (see Table 1). Breaker interrupting 9 kA at 43·4 kV recovery voltage.



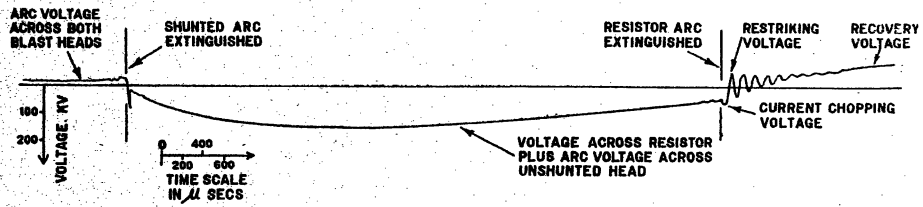
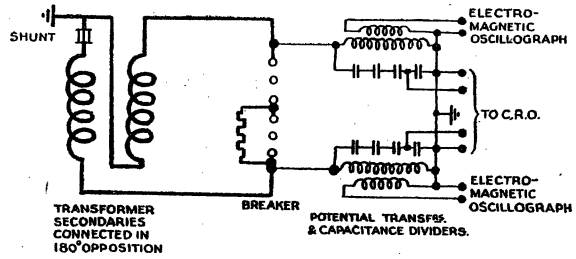


Fig. 13.—Cathode-ray oscillogram of Test 443 (see Table 1). Breaker interrupting 1·79 kA at 130 kV recovery voltage. On the actual test two C.R.O. records were taken as shown in the circuit diagram. The above is a reproduction of one C.R.O. with the voltage scale showing total voltage across breaker. For electromagnetic oscillogram of this test see Fig. 17.



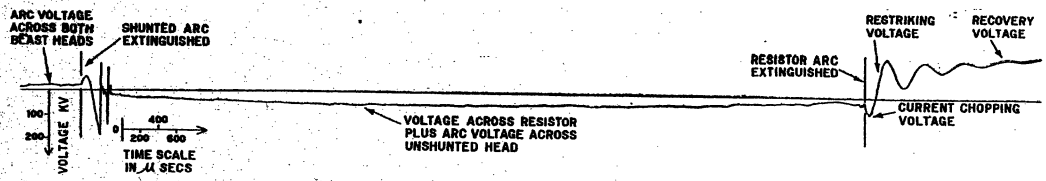


Fig. 14.—Cathode-ray oscillogram of Test 699 (see Table 1). Breaker interrupting 154 A at 121 kV recovery voltage.

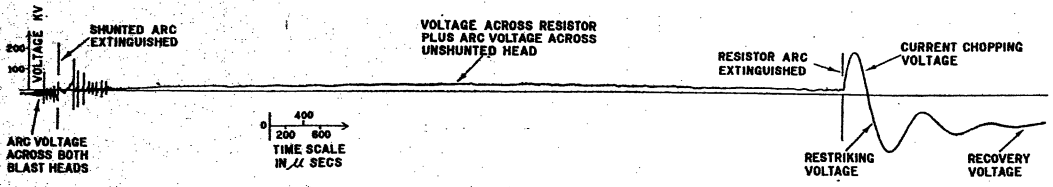
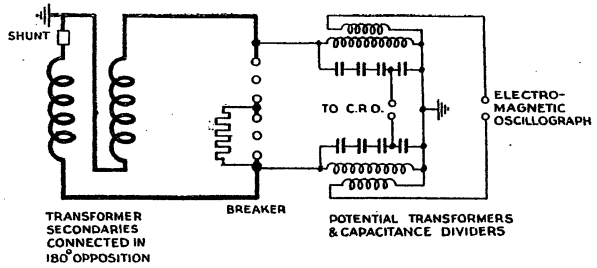


Fig. 15.—Cathode-ray oscillogram of Test 695 (see Table 1). Breaker interrupting 58 A at 119 kV recovery voltage.



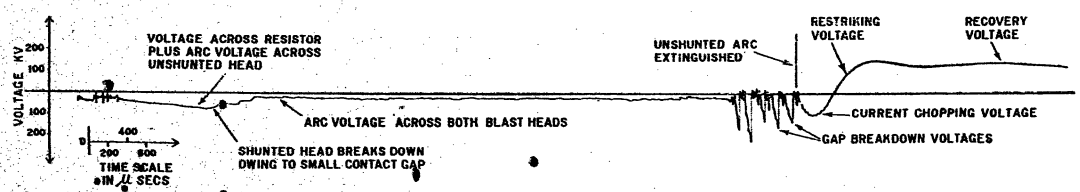


Fig. 16.—Cathode-ray oscillogram of Test 671 (see Table 1). Breaker interrupting 21 A at 112 kV recovery voltage. For electromagnetic oscillogram of this test see Fig. 18.

Table 1

SCHEDULE OF BREAK TESTS

TEST NUMBER	TEST QUANTITIES			PERFORMANCE TIMES				EQUIVALENT 3-PHASE RATING	
	BREAKING CURRENT		PHASE RECOVERY VOLTAGE	ARC DURATIONS SEC × 10^{-2}		TOTAL BREAK TIME, CYCLES		LINE RECOVERY VOLTAGE	SYMM MVA AT 132 kV
	SYMM kA	ASYM kA	kV	SHUNTED ARC	RESISTOR ARC	SHUNTED ARC	RESISTOR ARC	kV	
671 *†	0·021	0·021	112	0·94	—	2·90	—	129	4·7
672	0·021	0·021	110	1·7	—	3·25	—	127	4·6
673	0·021	0·021	113	1·3	—	3·05	—	130	4·7
694	0·060	0·060	118	0·55	—	2·60	—	136	14·1
695 *	0·058	0·058	119	0·29	0·87	2·45	2·90	137	13·8
696	0·057	0·057	119	1·3	—	2·85	—	137	13·5
697	0·156	0·158	121	0·98	—	2·75	—	140	37·8
698	0·154	0·155	119	0·58	0·77	2·50	2·90	137	36·5
699 *	0·154	0·155	121	0·75	0·75	2·60	3·00	140	37·3
431	0·449	0·463	140	1·5	—	3·10	—	162	126
432	0·458	0·463	140	2·0	0·72	2·80	3·15	162	128
433	0·449	0·454	140	1·1	1·70	2·60	3·45	162	126
435	0·884	0·884	135	1·0	0·58	2·95	3·25	156	238
436	0·865	0·865	135	1·5	0·67	3·15	3·50	156	233
437	0·865	0·865	135	1·5	0·75	3·20	3·60	156	233
439	1·57	1·59	134	1·1	0·64	2·85	3·15	155	420
440	1·57	1·59	131	1·7	0·58	3·20	3·50	151	410
441	1·57	1·59	133	1·0	—	2·85	—	154	418
443 *†	1·79	1·79	130	1·7	0·61	3·10	3·40	150	466
444	1·82	1·82	130	1·8	0·64	3·20	3·50	150	473
445	1·82	1·84	130	1·2	0·65	2·90	3·25	150	473
447	2·40	2·40	114	2·1	0·57	3·30	3·60	132	549
448	2·38	2·38	114	2·0	0·56	3·25	3·55	132	545
449	2·38	2·38	114	2·1	0·56	3·35	3·65	132	545
450	3·35	3·39	112	2·3	0·57	3·50	3·80	129	766
451	3·42	3·45	114	1·6	0·57	3·10	3·40	132	782
452	3·42	3·42	114	2·0	0·73	3·35	3·70	132	782
583	4·07	4·07	114	1·2	0·68	3·05	3·40	132	930
584	4·14	4·14	114	2·0	0·67	3·60	3·95	132	945
585	4·07	4·07	114	2·1	0·68	3·50	3·85	132	930
453	5·06	5·06	73·7	2·0	0·57	3·20	3·50	85	1155
454	5·06	5·11	73·7	1·4	0·64	3·00	3·30	85	1155
455	4·97	5·01	73·7	1·5	0·58	3·05	3·35	85	1135
456	5·50	5·89	77·9	1·3	0·57	2·90	3·20	90	1260
457	5·64	7·99	76·5	1·6	0·43	3·05	3·25	88	1290
458	5·64	7·31	75·2	1·4	—	2·95	—	87	1290
586	6·55	6·55	73·6	1·3	0·56	3·15	3·45	85	1500
587	6·43	6·43	74·8	0·56	0·56	2·70	3·00	86·5	1470
588	6·43	6·43	73·6	0·55	0·62	2·80	3·10	85	1470
460	7·18	7·25	59·6	1·4	0·57	3·00	3·30	69	1640
461	7·05	7·05	59·6	1·1	—	2·70	—	69	1610
462	7·18	7·25	57·8	1·3	0·43	3·00	3·20	66·8	1640
463	8·75	8·75	43·4	0·88	—	2·65	—	50·2	2000
464 *	9·00	9·08	43·4	1·2	0·44	2·80	3·00	50·2	2060
465	9·00	9·08	42·5	1·6	0·56	2·95	3·25	49	2060
589	11·50	11·50	43·3	0·27	0·48	2·60	2·90	50	2630
590	11·50	11·50	42·6	0·26	0·53	2·75	3·00	49·3	2630
591	11·50	11·50	43·3	0·81	0·54	3·00	3·25	50	2630

* Cathode-ray oscillograms of these tests are shown in Figs. 12–16.
† Electromagnetic oscillograms of these tests are shown in Figs. 17–20.

current at each of these voltages was increased up to the maximum output of the test plant.

Most of the test duties comprising three break tests were preceded by a reduced-voltage trial test, the results of which have not been tabulated.

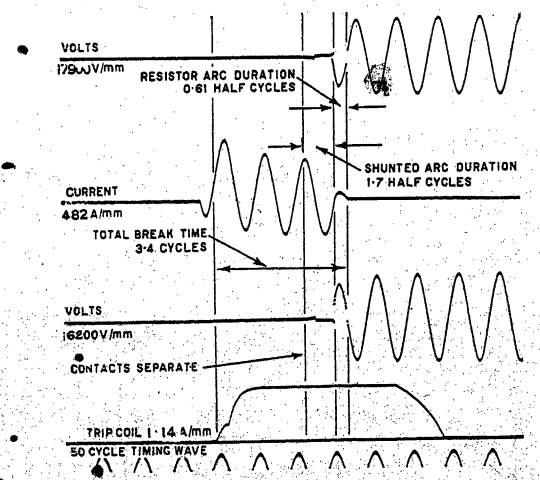


Fig. 17.—Oscillogram of break test (Test 443, see Table 1). Breaker interrupting 1·79 kA at 130 kV recovery voltage. For cathode-ray oscillogram of this test see Fig. 13.

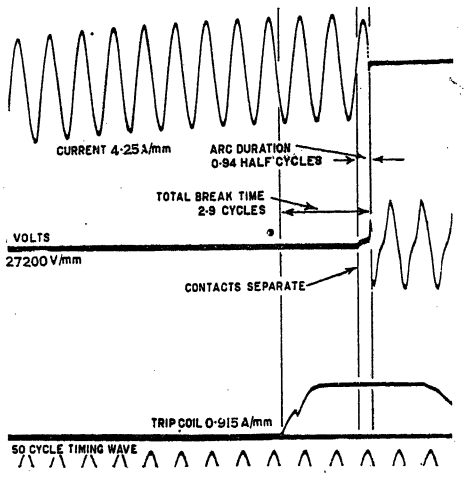


Fig. 18.—Oscillogram of break test (Test 671, see Table 1). Breaker interrupting 21 A at 112 kV recovery voltage. For cathode-ray oscillogram of this test see Fig. 16.

All break tests below 400 A were carried out at the maximum receiver pressure obtainable (250 lb/in^2 gauge), and for those above 400 A the receiver pressure was set at the lock-out value (200 lb/in^2 gauge).

Table 2 shows the results of three "make" tests on the series isolator.

Table 2

SCHEDULE OF "MAKE" TESTS

Test number	Test quantities	
	Applied voltage	Peak making current
	kV	kA
474*	83·3	1·63
466	63·0	7·64
469	48·6	17·3

* An electromagnetic oscillogram of this test is shown in Fig. 19.

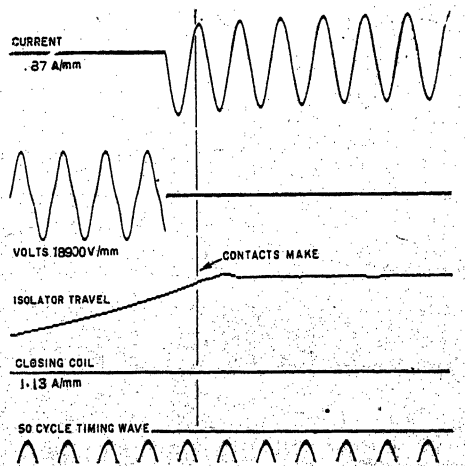


Fig. 19.—Oscillogram of make test (Test 474, see Table 2). Peak making current 1·63 kA. Applied voltage 83·3 kV.

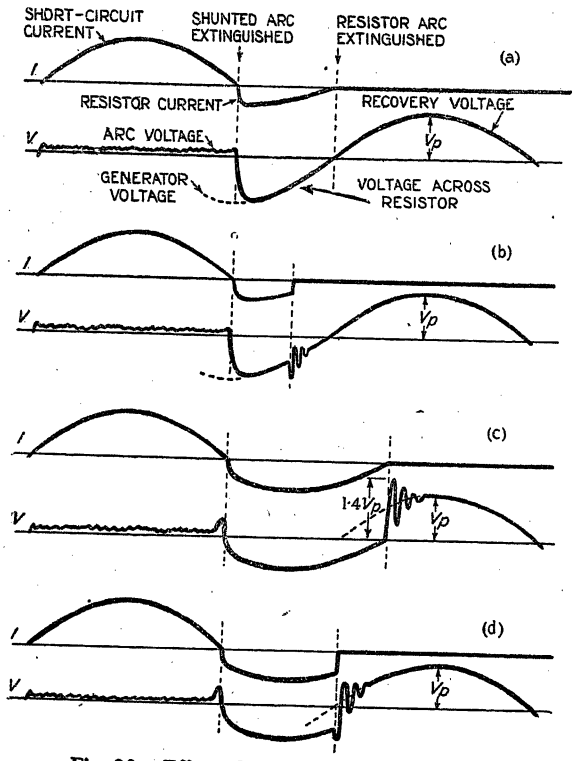


Fig. 20.—Effect of chopping resistor current.

(*a*) Interruption of low-inductance circuit, zero power factor. No current suppression.
(*b*) Interruption of low-inductance circuit, zero power factor. With current suppression.
(*c*) Interruption of high-inductance circuit, power factor = 0·08. No current suppression.
(*d*) Interruption of high-inductance circuit, power factor = 0·08. With current suppression.

(9.2) Discussion of Test Results

(9.2.1) Current-Chopping and Electric Strength of Nozzles.

The current-chopping which occurred at different values of breaking current can be seen from the cathode-ray oscillograms Figs. 12–16.

From Fig. 12, which was taken when breaking a current of 9 kA, it can be seen that there is practically no loop in the arc-voltage trace of the form shown at "A" in Fig. 1(*a*), and therefore negligible current-chopping occurred.

Fig. 13 also shows negligible signs of current-chopping when the breaker interrupted a current of 1·79 kA.

When the current was reduced to 154 A (see Fig. 14) a small loop in the voltage trace occurred, and at 58 A (Fig. 15) the voltage loop was very pronounced.

Owing to the fact that the unshunted blast head has been designed for electric strength only, and not for high breaking capacity, the effect of the air blast on the arc is comparatively mild, and it was not until the current was reduced to 21 A that multiple current-chopping occurred (Fig. 16).

The five restrikes of the unshunted gap which can be clearly seen on this oscillogram occurred at widely different voltages, and this confirms the variations in electric strength of the nozzles which are shown in Fig. 6.

(9.2.2) Interruption of Resistor Current, and the Effect of Chopping the Resistor Current.

The maximum value of the current through the resistor occurs when the circuit reactance is negligible compared with the ohmic value of the switching resistor. As the reactance of the circuit is increased, the chopping which takes place on interruption of the resistor current is more pronounced.

Figs. 12 and 14 show the effect of chopping the resistor current on low-inductance and high-inductance circuits, respectively.

To facilitate the analysis of these oscillograms Fig. 20 has been prepared, showing voltage and current traces which would be expected under the stated conditions.

Fig. 20(*a*) shows the ideal interruption of a heavy short-circuit current at zero power factor on a low-inductance circuit without current-chopping occurring when the resistor current is broken.

Under these conditions, when the shunted arc is extinguished, thus inserting the resistor into the circuit, the resistor current goes into phase with the generator voltage, because the reactance of the circuit is negligible by comparison with the resistance of the switching resistor.

Exactly one quarter-cycle later, both the resistor current and the generator voltage reach zero and the current is broken without initiating any restriking-voltage transient.

Fig. 20(*b*) shows the same circuit conditions, but here the resistor current is chopped and a small restriking-voltage transient is generated in the inductance of the circuit.

Fig. 20(*b*) is representative of the cathode-ray oscillogram in Fig. 12, which was recorded on a 9-kA test.

Fig. 20(*c*) illustrates the ideal interruption of a small current where the reactance of the test circuit has the same ohmic value as the shunt resistor of the breaker, i.e. where $X = R$.

Under these conditions, when the shunted arc is extinguished the resistor current takes up a power factor of 0·5 with respect to the generator voltage.

Therefore, when the resistor current is interrupted at zero the generator voltage is $0{\cdot}7\,V_p$, and a restriking transient voltage having a maximum value of $1{\cdot}4\,V_p$ can occur (assuming no damping).

Fig. 20(*d*) shows the effect of current-chopping in the same circuit. Here the current is suppressed at the time when the generator voltage is zero.

In this case, although the generator voltage is zero, the chopped current induces in the reactance of the circuit a voltage transient which appears across the breaker gaps.

As the circuit reactance is increased compared with the switching resistance, the power factor of the resistor current is reduced and the duration of the first loop of the resistor current is lengthened until, in the limiting case of infinite reactance without current-chopping, it would equal one half-cycle and the transient voltage could rise to a value of $2\,V_p$.

Experience of many tests has shown that the maximum peak restriking-voltage at resistor-current interruption never exceeds $1{\cdot}25\,V_p$.

Fig. 20(*d*) is representative of the cathode-ray oscillogram in Fig. 14, which was recorded on a test at 154 A.

(9.2.3) "Making" Tests.

The "making" tests showed that it is impossible to obtain fully asymmetrical currents on closing high-voltage air-blast breakers where the circuit is closed on the air-break isolating switch. This is because the voltage strikes across the break whilst there are still several inches of gap, and thus must occur at or near a voltage peak. The reason for this can be understood by considering a 132-kV breaker in which the peak voltage can strike across the isolator when the gap is approximately 8 in.

Assume the worst case of a voltage peak occurring with a gap fractionally above 8 in, so that an arc does not occur at that peak. For a closing speed of 20 ft/s the gap will continue to shorten at the rate of 2·4 in per half-cycle, and the voltage will pass through zero and rise up towards a maximum of the opposite polarity. After 0·0085 sec the gap will have shortened to 6 in, and the voltage will have risen to the flashover value and initiated

the circuit current. This will occur 53 electrical degrees after voltage zero, giving only a small amount of asymmetry.

The contact-burning on such "making" tests is very slight and there is no tendency for the arc to wander and cause flashover to neighbouring apparatus or parts of the breaker.

(10) RESISTANCE SWITCHING AND TWO-PART TESTING

Full-scale breaking-capacity tests cannot be carried out on h.b.c. circuit-breakers, owing to limitations of size of existing test plants. In such circumstances it is usual to carry out "two-part testing," comprising tests at rated voltage and the maximum plant output current at that voltage, supplemented by tests at the rated breaking-capacity current at a reduced voltage which is the maximum available at that current. Although experience has shown such testing to be approximately true for oil circuit-breakers, it cannot be considered valid for air-blast breakers unless certain conditions are met.

The reduced voltage can be offset by reducing the air pressure, but no data are generally available enabling a decision to be made as to what reduction in air pressure is equivalent to a given reduction in voltage, or what is the exact influence of the changed mechanical performance of the breaker brought about by the reduced air pressure.

Where multiple series breaks are used the reduced voltage can be offset by testing each break separately. A test carried out under these conditions can be considered exactly equivalent to full-scale tests, provided the following conditions are imposed on the break undergoing test:—

(*a*) The current must equal the rated breaking-capacity current.

(*b*) The interference of all breaks one on another must be the same, e.g. where all breaks are supplied from one source of compressed air.

(*c*) The restriking transient across the break under test must be the same in shape and magnitude as it would be if all breaks were being tested in series at full voltage. This also applies to the start of the transient when it is initiated by pre-zero current suppression [shown at "A" in Fig. 1(*a*)].

(*d*) The recovery voltage across the break under test must be the same in amplitude as it would be if all breaks were being tested in series at full voltage.

Condition (*a*) is easily arranged by adjusting the circuit reactance.

Condition (*b*) can usually be met by arranging for all breaks to open and blast, and by short-circuiting all but the one break on which it is required to break current.

Conditions (*c*) and (*d*) can be met by ensuring that the ohmic value of the fixed impedances which are shunted across the multiple breaks (to ensure equal voltage distribution) are small compared with the surge impedance of the circuit comprising the reactance and all stray capacitances which determine the inherent restriking transient of the circuit. It must also be small compared with the post-arc resistance of the gap.

Although it is theoretically possible to achieve this by means of capacitances across the breaks, the values required are impracticably large. The values usually employed do no more than ensure equal division across the breaks of whatever transient is generated by the circuit, which transient varies with the different circuits required for full-scale and two-part testing. The most practicable method is to tap the resistor used for resistance switching across the breaks. When sufficiently low values are used, the restriking transient and recovery voltage are dependent only upon:—

(*a*) The applied voltage.

(*b*) The circuit reactance limiting the short-circuit current.

(*c*) The switching resistance.

The percentage impressed across each break varies directly as the proportion of the resistance across that break.

The restriking transient and recovery voltage are substantially independent of:—

(*d*) The various capacitances of the circuit.

(*e*) The post-arc conductivity of the break.

(*f*) The conditions of earthing of the supply system or fault as they affect the voltage distribution across the breaks.

Fig. 21 shows a multi-break breaker with four breaks, two being shunted by switching resistors and two being unshunted.

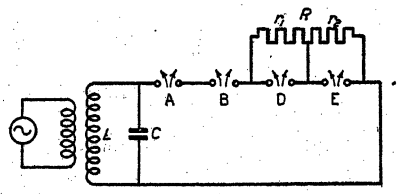


Fig. 21.—Multi-break breaker with tapped resistor.

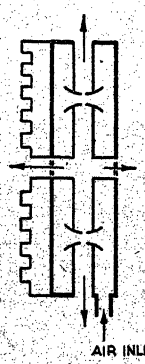
$r_1 = r_2 = 150\,\Omega$. $L = 0{\cdot}0635$ H.
$R = r_1 + r_2 = 300\,\Omega$. $C = 4\,000\ \mu\mu$F.

Table 3

SCHEDULE OF BREAK TESTS ON DOUBLE-BREAK BLAST HEAD, SHOWING RESULTS OF FULL-SCALE AND UNIT TESTING

FULL-SCALE TESTING OF BOTH BREAKS IN SERIES			
Test No.	Breaking current	Recovery voltage	Remarks
	symm. kA	kV	
822	2·06	54·7	Cleared
823	2·81	52·2	Cleared
824	2·81*	53·8	Failed
781	3·6	56·3	Failed

* Minimum breaking current for failure.



UNIT TESTING OF EACH BREAK			
Test No.	Breaking current	Recovery voltage	Remarks
	symm. kA	kV	
814	2·44	26·4	Cleared
818	2·51	27·2	Cleared
820	2·92*	28·3	Failed
785	3·15	27·0	Failed
784	3·23	28·6	Cleared
783	3·29	29·6	Cleared
806	7·61	31·6	Cleared
807	7·75	31·6	Cleared

Assume a single-phase circuit to give 6·6 kA at 132 kV and to give an inherent restriking transient of 10 kc/s.

The inductance of the circuit is 0·0635 H to give 6·6 kA at 132 kV.

The value of C to give 10 kc/s is 4 000 $\mu\mu$F.

Therefore the surge impedance is 4 000 ohms.

The resistance of 300 ohms shunting the breaks is less than 1/13th of the surge impedance and thus the magnitude and shape of current-chopping and restriking transient voltages are determined thereby.

If, therefore, each break "D" and "E" is tested in turn with the other break and its resistor short-circuited and with rated current flowing, but at half voltage, then the performance of each break should be identical with its performance when tested in series at full rated voltage.

The E.R.A. have suggested calling such testing "unit testing," and the authors would like to support this proposal.

Table 3 shows results of "full scale" and "unit" tests applied to a two-break radial-flow double-blast head of the type shown in Fig. 10. For this type of head, air is admitted to the lower chamber surrounding the lower break and then passes through orifices past the middle exhaust chamber to feed the top break. This results in a lower air pressure at the top break, with a consequent reduction in breaking capacity as compared with the lower break.

In commercial designs this is usually compensated by an increase in nozzle diameter and break distance for the top break.

For these tests, however, both breaks were made physically identical, with the result that the ultimate breaking capacity of the lower break is much higher than that of the top break.

Comparing the test results, it will be seen that the two breaks in series failed at approximately the same current as, and double the voltage of, the top or poorer of the two breaks alone. Had the bottom break been blocked up or missing, or had the bottom break alone been tested, entirely erroneous conclusions would have been reached.

As a matter of interest it was later proved that by increasing the nozzle diameter of the top break by 50% and the break distance by 20%, the top break was made as good as the bottom break and the breaking capacity of the two in series was more than doubled.

(11) PROPOSED TYPE TESTS TO PROVE BREAKING CAPACITY

A series of breaking-capacity type tests should prove that the breaker can interrupt any current up to its rated capacity on any type of circuit. Such tests can be divided under three headings:—

(*a*) Tests at full breaking capacity.

(*b*) Tests at the value of short-circuit current which gives most onerous conditions for the operation of the unshunted head breaking the resistor current. (For breakers with resistance switching only.)

(*c*) Tests to prove that the breaker limits, to permissible values, switching surge-voltages caused by current-chopping or the breaking of capacitive currents.

Some further explanation is required with respect to (*b*) above. When interrupting heavy short-circuit currents the ohmic value of the switching resistor is high compared with the ohmic value of the reactance of the circuit, so that the resistor current is approximately at unity power factor and interruption therefore occurs with a very small voltage transient. As the value of fault current being interrupted is reduced by increasing the system reactance, the power factor of the resistor current decreases, but so does the value of the current, until with very high values of reactance the resistor current is practically at zero power factor, but it is also very small in magnitude.

It is found that the most onerous combination occurs where the ohmic value of the system reactance is equal to the ohmic value of the switching resistor.

The following series of test duties is therefore proposed.

Duty 1.

B–3–MB–3–MB at rated symmetrical breaking current, peak making current and voltage.

Duty 2.

B–3–B–3–B at rated asymmetrical breaking current and voltage.

Duty 3.

B–3–B–3–B at a current where the system reactance in ohms equals the ohmic value of the switching resistor.

Duty 4.

B–3–B–3–B– – – – 3–B (20 tests) at a small value of current at which cathode-ray oscillograms show multiple current-chopping to take place. (Magnetic and cathode-ray oscillograms to be taken on 1st, 10th and 20th tests only.)

Duties 1, 2 and 3 should be carried out at the minimum air pressure for short-circuit tests or lock-out pressure.

Duty 4 should be carried out at an air pressure equivalent to the safety-valve setting.

For Duty 4 the breaker should be shunted by a sphere gap or equivalent measuring device set to flash-over at the maximum permitted value of surge voltage. It is suggested that eventually this value for a given rated voltage should be tabulated in the appropriate British Standard Specification.

No flashover of the sphere gap or over the breaker heads or insulators should take place.

Where full-scale tests cannot be carried out and where the breaker is of the multi-break type with resistance switching, "unit testing" should be adopted in which Duties 1 and 2 should be split up as follows:—

Duty 1(*a*).

B–3–MB–3–MB on each break at rated symmetrical breaking current and peak making current, at a voltage equal to line voltage divided by the number of breaks.

Duty 1(*b*).

B–3–MB–3–MB at rated voltage across all breaks in series and the maximum symmetrical breaking current and peak making current the plant can give at that voltage.

Duty 2.

B–3–B–3–B as 1(*a*) but at rated asymmetrical breaking current.

(12) CONCLUSIONS

(*a*) An air-blast circuit-breaker, like an oil circuit-breaker, causes over-voltages when it breaks a circuit under certain conditions.

(*b*) The prospective value of the over-voltages depends upon:—

(i) The circuit constants, i.e. inductance, capacitance and resistance.

(ii) The rate at which the arc is de-ionized.

(*c*) Under conditions very often realized in practice, the prospective value of such over-voltages can be dangerously high, and the actual value reached is limited only by restriking of the breaker gap.

(*d*) The breaker gap thus not only has to be proportioned to break its rated breaking current, but also to limit, by restriking, the values reached by switching over-voltages.

(*e*) The breaking capacity and electric strength of a nozzle are

interdependent, unless the restriking-voltage transient can also be controlled.

(*f*) The restriking transient can be modified by means of resistance switching, so that by its introduction the breaking capacity and electric strength of the breaker can be controlled individually and independently.

(*g*) By combining resistance switching with series multi-breaks, the distribution and exact shape of the restriking transient across each break can be accurately controlled. This means that "unit testing" of such breakers is completely valid. This will greatly increase the scope of existing test plants for testing h.b.c. breakers.

(*h*) The breaking-capacity type tests given in B.S. 116 for oil circuit-breakers are not entirely satisfactory for air-blast breakers. Amongst several minor changes it is necessary to add a test duty to prove that the breaker adequately limits switching over-voltages.

The switching over-voltage which is most convenient to produce on test plants is that due to current-chopping in an inductive circuit. The voltage-limiting effect of the breaker can be demonstrated by taking a series of breaking tests at a current at which multiple current-chopping occurs.

A duty comprising only three tests is considered inadequate to demonstrate the capability of the breaker to limit over-voltages, and it is suggested that 20 tests should be included. These should be sufficient to take care both of the variations in arc length at final interruption and also the statistical nature of the breakdown of air-gaps under rapidly applied voltages.

(13) ACKNOWLEDGMENTS

The authors wish to express their thanks to the British Thomson-Houston Co., Ltd., for permission to publish the results of tests which were undertaken to check the conclusions reached.

All the breaking-capacity tests were carried out at the testing station of the Switchgear Testing Co., the staff of which rendered a great deal of assistance, especially in the reproduction of oscillograms for publication.

The authors would also like to pay tribute to the quantitative work of the British Electrical and Allied Industries Research Association,* on the relationships of the various factors entering into the performance of air-blast breaker nozzles. This has formed the basis of all experimental work undertaken.

* CASSIE, A. M.: "Arc Rupture and Circuit Severity: A New Theory," International Conference on Large High-Tension Electric Systems, 1939, Paper No. 102.

DISCUSSION ON THE ABOVE TWO PAPERS BEFORE THE INSTITUTION, 30TH MARCH, 1944

Mr. C. W. Marshall: These papers indicate the reactions of switchgear designers to the potential effects of switching by air-blast circuit-breakers, and a fair warning is given to supply authorities that at some points on most power systems high transient voltages may be created when faults are being rapidly cleared. The two papers explore common ground in their analysis of the performance of circuit-breakers, but they differ profoundly on the practical solution of the over-voltage problem.

Messrs. Harle and Wild show how the rate of rise of restriking voltage can be calculated in terms of simple measurable circuit constants, and they give the limiting rates of rise which can be dealt with by commercial air-blast circuit-breakers. Supply engineers will doubtless be grateful for the clear and valuable statement of the basic calculation of R.R.R.V., but will probably be less satisfied with the prospect of having to make natural frequency surveys of their networks, or with the suggestion that reactors should be arranged in such a way as to avoid high natural frequencies, unless this can be done without impairing their effectiveness as short-circuit current reducers.

Messrs. Cox and Wilcox have produced what appears to be a general solution in the form of a resistance circuit-breaker which ensures that the R.R.R.V. will not exceed the clearing capacity of the unit, and that the transient voltages impressed on the apparatus will be innocuous. This manifest advantage is obtained at the cost of some complication, which may be viewed unfavourably by supply engineers who remember the weaknesses of oil circuit-breakers incorporating resistance switching. Generally, however, it will be conceded that the authors have made a notable contribution towards scientific circuit-control.

In Section 12(*c*) Messrs. Cox and Wilcox state that under conditions often realized in practice the prospective value of the over-voltages in question can be dangerously high. On the Grid all the 132-kV circuit-breakers now have arc-control devices of one kind or another. In the course of 15 years' experience, 3 cases of flashover of 26-in rod gaps have come to my notice; two were due to the switching-out of a transformer on no-load, and the third to switching-out a 132-kV line incorporating a current-limiting reactor. In no case were any of the over-voltages due to apparatus failures. 132-kV circuit-breakers controlling 15-MVA capacity compensating reactors have shown signs of being subjected to abnormal arcing conditions, although working at only 1% of their rating, the oil rapidly becoming carbon-laden after a few operations. In these particular applications, too, flashing-over of the neutral bushings was quite common when these were insulated.

A further interesting practical case is that of the switching-out of 66-kV cables. In one case where the peak-charging current is about 100 amp, we have on several occasions seriously damaged the arcing control devices, although without causing any widespread disaster. These experiences, although apparently insignificant in relation to the vast number of switching operations on the Grid, emphasize the value of the investigations which the authors have carried out. The C.E.B. has co-operated with switchgear manufacturers and with the E.R.A. in elucidating such cases, and will continue to do so, because I do feel that it is the duty of those concerned with supply to follow up the actual work of the testing stations and switch designers. In this connection, I am very glad to see the generous tribute paid to those E.R.A. investigators who have been working on circuit-breakers. They have done remarkably good and original work with comparatively weak testing plant, and it must be very satisfying to them to find their figures fully corroborated by the powerful equipment available in the testing stations.

The authors' suggestions for test duties appear to be in accordance with practical requirements, and should safeguard users from untoward experiences in field service. I suggest that it might be possible to spread out the 20 tests proposed by Messrs. Cox and Wilcox at uniform intervals over the current wave. That would make it the more certain that the most severe conditions were obtained.

Both papers indicate that the control of natural frequency by capacitance is hopelessly uneconomic, but there are developments outside the switchgear province which suggest the contrary. First, the development of high-voltage cables with very thin dielectrics and high capacitance will probably lead them to be more frequently incorporated in substation designs. It is quite common practice to put in a length of cable at overhead-line terminals with the single object of limiting the severity of lightning surges. There seems to be a good case for incorporating cables in stations with a view to improving the arrangement of apparatus and the accommodation of current transformers, and, in addition, to providing a measure of natural-frequency control. The

second possibility is that materials with very high dielectric constants, of the order of many thousands, are now available in high-frequency applications and it should be possible to employ them in power capacitors.

Mr. A. R. Blandford: In a recent paper before The Institution, I made a plea for greater collaboration between testing stations and the supply industry, with a view to establishing test values which would meet all normal situations. This plea was made in the interests of economy and not, as now seems to be the case, for the purpose of discriminating between oil and air-blast circuit-breakers. Up to the present, the air-blast breaker has been tested under conditions identical to those used for oil circuit-breakers. This may provide an unnecessarily high safety factor, particularly as one Continental manufacturer openly declares that he conducts his testing at the comparatively low frequency of 10 000 c/s. Messrs. Harle and Wild's proposals in Fig. 10 are, however, very welcome, but I do not think that the survey of the conditions prevailing on systems in this country is yet sufficiently complete, and for this reason they may have shown excessive and premature zeal in making their proposals.

Test experience with other air-blast circuit-breakers is at variance with curve 7 in Fig. 3. Here, it seems, there is a tendency towards generalizing on the basis of tests on one type of design, which may not be wise. This curve assumes a different shape for different designs and voltages, and in fact a 132-kV air-blast circuit-breaker recently tested showed satisfactory operation at 4 300 V/μs on 10% and 6 100 V/μs at 100% test. This is a departure from the shape of the curve reproduced by the authors, and, of course, affects curve 4 in Fig. 3.

It is surprising to find so much space devoted to the plain-break oil circuit-breaker. How many h.v. breakers of this type have the authors recently installed?

Fig. 4 compares oil and air-blast circuit-breakers, and in each case shows the effect of the restriking voltages at different duty cycles. These curves are set out in rather misleading fashion, as, when an air-blast circuit-breaker of the axial-blast type gives 2 half-cycles of arcing, it does so either because the current zero is inopportune or because it has very nearly reached its failure point. The latter condition is borne out by the authors' curves, from which it may be assumed that all air-blast circuit-breakers are operating under a condition of failure at 100% duty cycle at 800 V/μs, which is, of course, incorrect. Perhaps the authors do not intend this interpretation to be put on the curves; if so, it would have been preferable to extend the base of the curve up to a higher R.R.R.V. showing circuit-breaker failure rates more comparable with those obtained on test.

In Section 11.1.1, it is suggested that a tangent should be drawn to the first peak exceeding 80% of the normal 50-c/s peak recovery voltage. I suggest that this is far too high, as peaks not exceeding 20% of the 50-c/s peak recovery voltage have been known to be the cause of failures on air-blast circuit-breakers.

Messrs. Cox and Wilcox describe a 132-kV air-blast breaker in which resistance switching is incorporated. It is not quite clear whether this has been incorporated mainly to improve the efficiency of the breaker or to restrict peak over-voltages in service. At the end of Section 2 the authors suggest that the non-incorporation of resistances is a "brute force" method of extinguishing the arc. This is not borne out by operating data obtained on other air-blast breakers.

The 132-kV circuit-breaker to which I have already referred did not have resistors. It was a 2-break circuit-breaker—not 2 breaks and 2 resistance breaks, but simply 2 breaks without resistances—and it operated at the same pressure as the authors' breaker, 250 lb/in^2 nominal. It operated satisfactorily up to 187 kV at 750 amp and at 132 kV at the 10% duty cycle. For the same maximum currents as those given by the authors it has a lower air consumption, hence the term "brute force" is not justified.

Dr. W. B. Whitney: These two papers, with the recent paper by Mr. Blandford, have been a very great encouragement to those who have faith in the future of the gas-blast circuit-breaker.

The problems connected with air-blast breakers can be classified under the heads of design, rating and specification, and proving.

With regard to the first, research and design have to meet and overcome functional difficulties, which in some oil circuit-breakers may be masked and which early research on air-blast breakers brought to light. The principal difficulties are: sensitivity to the net effects of such circuit components as affect high-frequency voltage transients, and current chopping, which occurs also in oil circuit-breakers although it was long unsuspected there.

Under the second head, the rating of air-blast circuit-breakers calls for a suitable specification to ensure that, on rating tests, the breaker will meet the worst severity demands (h.f. and l.f.) likely to be made on it at its rated kVA and kV when later it is installed in any network.

Thirdly, the proving of an air-blast breaker in relation to such a specification implies a suitable testing technique and, where extrapolation has to be used, knowledge of the laws involved; it also requires the proper set-up of test-circuit parameters.

I notice that both papers fail to mention the importance of securing adequate arc duration in air-blast tests. This precaution needs stressing because in such breakers, the heated gases from arcing on the high-pressure side of the throat, have to be eliminated before current zero, and because their quantity increases with arc duration. Fig. A, which is a diagram based on

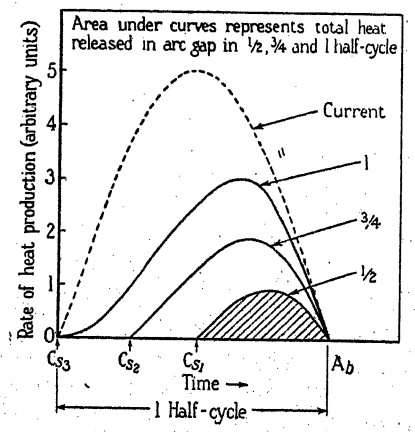


Fig. A.—Dependence of total heat release on arc duration.

the energy release in a steadily-opening gap during a half-cycle of current, indicates the wide variation in the rate and total quantity of heat generation which can occur depending on the point (C_s) of the commencement of arcing in relation to the current zero (A_b). Alternatively, if there is sufficient fundamental knowledge of the behaviour of gas-blast breakers, it should be possible to tell, from a test in which there is not a full half-cycle of arcing, whether the breaker will clear when C_s takes place early in an asymmetrical wave.

The paper by Messrs. Harle and Wild is a valuable contribution to the problem of assessing circuit severity on the basis of a straightforward race between rising voltage and recovery of dielectric strength by the gap, and is a friendly challenge to the Cassie energy-balance theory* (referred to in both papers) to justify itself by producing a better yard-stick for the purpose.

* Cassie, A. M., *loc. cit.*

This yard-stick should be able to measure the circuit severity with which an air-blast breaker of the axial type has to deal, without the ambiguities associated with the R.R.R.V. theory, and I am confident that the new theory will provide a simpler relationship between the effort demanded of an air-blast breaker and the severity it has to meet.

It is clear that the development and utilization of resistance switching and the possibilities of adjusting the breaker effort, by selection of blast pressure and nozzle diameter, provide all the tools the designer needs to deal with the conditions of circuit severity which can occur, and the paper by Messrs. Cox and Wilcox shows the advance already achieved in this direction.

Mr. C. H. Flurscheim: With regard to the proposals put forward for a new air-blast circuit-breaker specification, it should be remembered that even with oil breakers the validity of ratings based on B.S.116 is dependent on a wide background of development testing. I do not consider it will be found either practicable or desirable to introduce into a new specification clauses endeavouring to cover a wide additional range of possibilities. I believe rather that these should still form part of the considerable development programme essential with any new class of circuit-breaker design.

As regards restriking phenomena, the effect of these on air-blast breakers varies very widely with the design and also to some extent with the restriking wave form, even given similar rates of rise. An attempt to introduce them as a new rating criterion can only be considered as a retrograde step in the art, if thereby the application of air-blast circuit-breakers is to be more limited than that of oil interruptors, and it should be sufficient at the present time to include the inherent testing-circuit conditions in the test reports issued.

The difficulties attendant on drawing up a wider specification must be evident when the variety of methods of interruption with air-blast are considered. These include breakers without resistance damping, with linear resistors inserted through a gap or permanently shunted across some section of the breaker. These will all respond differently to restriking phenomena and will require a different technique in applying the desirable feature of unit testing with larger types. Yet a further solution is possible involving the permanent shunting of the interrupter element with a non-linear ceramic resistor such as Metrosil, in which the resistance decreases very rapidly with rise in voltage. The follow-through resistance current is then so suppressed towards current zero by the characteristics of the material that it can be interrupted without air-blast by the series automatic isolator normally required. The resistance can also be controlled so that it can suppress entirely any attempt by the circuit-breaker to produce over-voltage, and it can, if required, modify the normal restriking voltage transient.

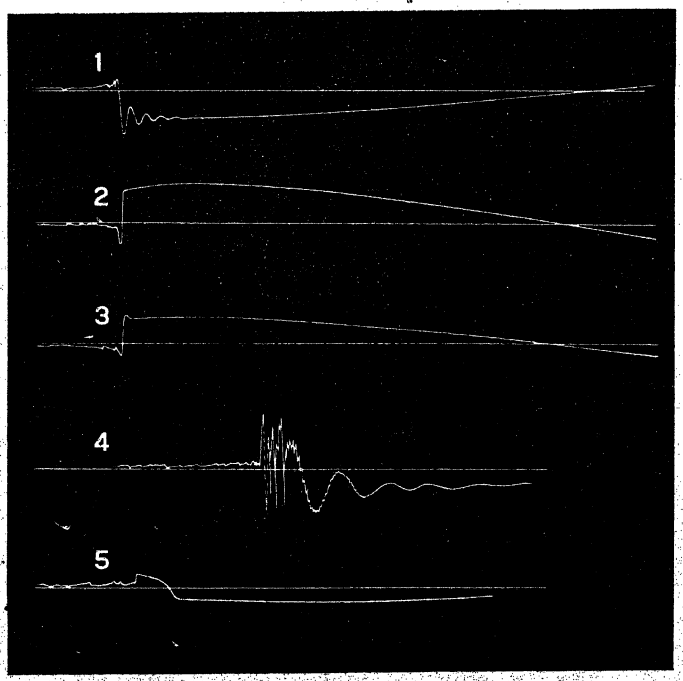


Fig. B.—Cathode-ray oscillograms for a h.v. air-blast circuit-breaker.

Fig. B shows cathode-ray oscillograms obtained on a high-voltage air-blast circuit-breaker under different operating conditions. Curve 1 shows interruption of a short-circuit without resistance. Curve 2 shows the same test for the first phase to clear with a non-linear resistance across the breaker, while curve 3 shows the second phase to clear in which the 50-c/s peak voltage is lower and the damping therefore less complete. Curve 4 shows interruption of light inductive current without damping, and curve 5 the same test repeated with the non-linear resistor in circuit.

Mr. W. A. McNeill: In the first paper, Messrs. Harle and Wild have weakened an otherwise excellent review of the influence of network conditions on the performance of circuit-breakers by assuming that restriking rate is the complete criterion of circuit severity. They have glossed over the difficulties of interpreting the relationship between single- and multi-frequency transients, and have also assumed, as indicated by Mr. Blandford, that voltage peaks of less than 80% of the 50-c/s crest can be ignored. On these and other grounds, I cannot support their suggestion that rate of rise should be included in the rating of air-blast breakers, and I think that an analysis of their own data in the paper shows that, in general, the severities of the British testing stations represent the worst conditions usually encountered in service. From the point of view of proving the design of air-blast breakers, I should prefer to approach the problem from another angle, and obtain co-ordination of the testing conditions by agreement amongst the testing authorities.

Turning to the authors' proposals for unit testing in Section 11.3, I view the proposed scale-model tests with some misgivings and I foresee considerable difficulty in incorporating such tests in a British Standard. I should like to know the precise theoretical justification for the performance ratio mentioned, and why this factor should be less than unity. For three reasons, the conclusions drawn from the authors' tests are open to question. Voltage distribution in the test described appears to have been judged from cathode-ray oscillograph records; in my experience the recording equipment itself introduces unbalancing capacitance. Secondly, insufficient data are given to determine whether the air flow and pressure conditions were identical for each break. Thirdly, the data are insufficient to prove that the assumed relationship between breaking capacity and rate of rise is correct over a wide range.

In the second paper, Messrs. Cox and Wilcox have made out a very good case for the universal application of resistance switching, and I agree that it has many virtues up to 33 kV, but I cannot agree that its incorporation is indispensable at higher voltages. If the methods of "brute force" referred to by the authors would include the use of, say, 25% more air than they mention, and if by such methods simplicity of construction and ease of maintenance are achieved, then I prefer brute force, provided, of course, it is not accompanied by crass ignorance.

Also, I strongly disagree with the statement that capacitance control of voltage distribution is impracticable where unit construction is applied. By suitable arrangement of the interrupting heads, adequate balancing capacitance can be achieved;

tests have shown that the influence of post-arc conductivity is negligible.

The authors appear to have exaggerated the problem of current chopping. Their proposed remedy, a gap of low electric strength, is certainly effective in limiting the voltage appearing across the breaker, but it may introduce other troubles. If such a gap breaks down repeatedly when interrupting charging current of capacitance circuits, dangerous voltage rises may occur. Where the suppression of current-chopping voltages is necessary—and the case for the universal application of any preventive means is not yet proved—I prefer a voltage-dependent resistance of the Metrosil type already mentioned. It is hoped to describe the application of this method more fully when patent proceedings have been completed.

Regarding the design of the nozzle given in the paper, the method of calibration is very interesting and would certainly be useful, but I cannot agree with the assertion that the gap is necessarily completely de-ionized before the transient peak is reached, and as far as the consistency of the nozzle is concerned a study of Fig. 6 would suggest that the nozzle is consistent only in its inconsistency. I prefer a double nozzle of the type incorporating a convergent-divergent orifice.

Mr. J. S. Forrest: In the past, information on the rate of rise of restriking voltage has not been readily accessible, and the data given by Messrs. Harle and Wild for systems operating at various voltages and for testing stations will be welcomed by users of switchgear.

In Messrs. Cox and Wilcox's paper, I was very interested in the ingenious test set-up shown in Fig. 5, and in the pin-hole photograph of the sparkover shown in Fig. 7—it may be worth mentioning that there is an optimum size of pin-hole. It is rather disconcerting to find that the measured breakdown voltages exhibit such a large spread, amounting to 50%. The authors dismiss this by saying that it is an inherent feature of the breakdown of air at high pressure. There is no doubt, however, that any such inconsistency in an experimental investigation means that some variable is not properly controlled. In the present case, I suggest that if the authors took high-voltage cathode-ray oscillograms showing the time lag to breakdown and the breakdown voltage, then the reason for the variation might become apparent. It might also be worth while to determine whether the consistency of sparkover voltage was improved by the presence of some radium salt on the spark-gap.

I should like to refer to a general point in the design of air-blast switchgear. It is often found that a newly developed equipment fulfils all major requirements, but fails to meet some apparently trivial service condition. For example, an air-blast switch might successfully clear 2½ million kVA in a few cycles, but would fail to withstand the British climate and the normal service voltage for a few years. Quite a large proportion of breakdowns on outdoor switchgear are due to the flashover of the external porcelain insulators. The conventional oil circuit-breaker has two external porcelains per phase, but a typical air-blast circuit-breaker, e.g. Fig. 9 in Messrs. Cox and Wilcox's paper, has six insulators per phase between live metal and earth. Furthermore, the potential distribution on these insulators is not so good as in the case of the usual condenser bushings. Supply engineers expect to obtain at least as good service from air-blast as from oil circuit-breakers, and it follows that the designer must provide insulators having three times as good a performance if he is going to use three times the number of insulators. This can be achieved by using adequate leakage distances, more than one inch per kV of system voltage. Recent developments, however, indicate that a more effective method of improving insulation performance is to use a semi-conducting glaze on the external and internal surfaces of the insulator so that the steady leakage current is about 1 milliamp per insulator; in other words, to use "stabilized" insulators. I should be interested to have Messrs. Cox and Wilcox's views on this possibility.

Mr. J. S. Cliff: The general principles of the MVA/R.R.R.V. characteristics of air-blast circuit-breakers are now fairly well understood, and, as the paper by Messrs. Harle and Wild shows, these must be taken into account in the rating and testing of such interrupters. The problem of rating resolves itself into determining what is a fair R.R.R.V. to take for a given MVA rating at a given service voltage. This must obviously depend upon the characteristics of the supply networks, and already sufficient work has been done to show how difficult this selection is going to be, since the R.R.R.V. in service varies over a very wide range.

The first possible solution to this problem is to rate the circuit-breakers for the highest R.R.R.V. values encountered in service. Most of the service data so far collected have been concerned with the maximum values obtainable, and these, as the authors demonstrate, are usually associated with transformers or reactors, and in many cases reach very high values provided that there are no overhead lines or cables attached to the circuit, and also assuming that there is no parallel load. Circuit-breaker operation under these conditions is very rare, particularly at the medium voltage at which many circuits are usually coupled to the busbars. A further difficulty arises during testing for these conditions, for, as will be seen by superimposing the curves of Fig. 11 on those of Fig. 10, the maximum R.R.R.V.'s in service are considerably greater than those on standard test circuits. It would thus be uneconomical to build, and difficult to test, circuit-breakers rated on the basis of the maximum rates obtainable in service.

To obtain a clear picture of the distribution of the R.R.R.V. with respect to short-circuits occurring during normal system operation will require a considerable amount of work, and calls for close collaboration between operating engineers and designers, but if simple, reliable, and economic designs are to be produced, this work must be undertaken. From general considerations, and the performance in service abroad of circuit-breakers having very poor R.R.R.V. characteristics as judged by British standards, it is clear that the severity of a very high percentage of the short-circuits is not very great, and this factor must be borne clearly in mind, otherwise we may be severely handicapped ourselves, particularly in competition with Continental products.

The third possible solution is to make the circuit-breaker performance independent of circuit severity. This can be done by shunting the arc with a resistance, and many such circuit-breakers are operating satisfactorily on medium-voltage circuits. Messrs. Cox and Wilcox have shown how it can be achieved for the higher voltages. To clear the resistance current additional breaks are necessary, thus making the design more expensive and complicated. Whether this is really necessary, and therefore justifiable, can only be proved by operating experience.

Mr. H. Trencham: In the paper by Messrs. Harle and Wild, the statement is made that air-blast breakers are highly sensitive to rate of rise of restriking voltage, but this does not cover the whole truth. Fig. 6 of the paper shows a characteristic in the form approximately of a hyperbola and confirms what the E.R.A. has told us, namely that the R.R.R.V. is not a true criterion of severity. It means that the sensitivity to rate of rise varies: the curve at one end is asymptotic to a constant R.R.R.V. when a small change in it may carry one over from success to failure, or vice versa; whereas at the other end it is asymptotic to a constant MVA value and breaking is virtually independent of the R.R.R.V. When, therefore, one engineer claims test results which show that the breaker is very sensitive, and another says that he found no

difference at all with changed R.R.R.V., they can both be telling the truth, but will be referring to different points on the characteristic curve.

Intermediately, the slope changes between these extremes and will be settled by the individual conditions of each case considered. These conditions involve the circuit constants (or natural frequency, if you will), the geometry of the breaker nozzle and the pressure of air used.

From the paper by Messrs. Cox and Wilcox it may be inferred that the hyperbolic characteristic curve of MVA against natural frequency provides the dominant factor which settles whether resistance switching is or is not necessary at any given breaking rating and voltage.

As regards the suggestion in Messrs. Harle and Wild's paper that the R.R.R.V be standardized for testing air-blast circuit-breakers, and referring to Fig. 10, the dotted lines appear to be portions of hyperbolae, but it is clear that they belong to different curves or to various sections of the curves. There is, however, no indication which purports to show that they are truly of general application or, on the other hand, are peculiar to some one form of breaker design. The figures indicated in this series of curves are very much lower than are reported for system conditions in the United States in a report by St. Clair and Adams on a survey of the systems of six power companies.

It is clear that the R.R.R.V. in one form or another must be taken into account in our tests, if only to secure that they are severe enough to give reasonable assurance of safe service. To introduce it as a factor in the choice of a circuit-breaker would do a disservice to the air-blast breaker. It has not been necessary in the application of oil breakers, and few operating engineers have time enough to analyse their systems in order to ascertain figures on which they would care to risk the safety of their systems, even if they were prepared to neglect the very frequent changes in connections and resulting natural frequencies which operating conditions impose.

It is a responsibility heretofore carried by manufacturers and will best remain so. In meeting that responsibility they will be well advised to push their designs as high as they can towards test plant conditions rather than pull them down as low as they dare towards system conditions, because these have changed and will change again. What is large enough for to-day may well be too small to-morrow, and time and trouble taken now may save many difficulties later on.

Mr. D. E. Lambert: Regarding the co-operation supply authorities can give in the development of air-blast circuit-breakers, Fig. 10 of Messrs. Harle and Wild's paper shows two sets of curves—one set indicating air-blast circuit-breaker characteristics, and the other the probable maximum system rates of rise of restriking voltage. Manufacturers are making steady progress in determining air-blast circuit-breaker characteristics, and any corresponding data which supply companies or the E.R.A. can give regarding system conditions will materially assist development and standardization of this class of circuit-breaker.

I agree with the authors that at the present stage of development of air-blast switchgear, resistance switching is desirable up to 33 kV, but for the higher voltages I believe that for all practical purposes a resistance can be avoided. This has been proved at 66 and 132 kV with the type of circuit-breaker shown by Messrs. Harle and Wild, which incorporated for 132 kV, multi-breaks, a suitable voltage limiting gap, and an appropriate construction of contacts to give a restricted arc length.

The two main arguments advanced in favour of resistance switching are: (*a*) a modification of rate of rise of restriking transient, and (*b*) a great reduction in air consumption. With regard to (*a*), where the rate of rise is too high to be dealt with by a single break without resistance switching, multi-breaks are utilized in such a way as to reduce the rate of rise so that the value per break can be dealt with easily. In respect to (*b*), the air consumption of an air-blast circuit-breaker is dependent on many factors, including the size of the nozzle (which in turn is related to the value of the short-circuit current to be broken), the pressure which is necessary to give the required dielectric strength within the circuit-breaker, the volume of the inflation spaces, the time for which the air is supplied for an operation of the circuit-breaker, and the air which is used for conditioning the insulation. Although it is generally admitted that the rate of flow of air can be less for a circuit-breaker embodying resistance switching, this factor does not seem to be the dominating one in respect to air consumption. In point of fact, the 132-kV circuit-breaker to which I have already referred, and which is not fitted with a resistance, has been subjected to short-circuit currents equal to those mentioned by the authors and with a total air consumption per make-break operation almost the same as that given by the authors. The supply of air is maintained until the series-break isolator arm has reached a safe clearance distance.

An interesting point in connection with test results given by Messrs. Cox and Wilcox is referred to in the last paragraph of Section 10. This shows that an increase in nozzle diameter of one break by 50 per cent (with its corresponding increase in air consumption) can double the breaking-capacity of the circuit-breaker. Previously, however, in Section 2, the "brute force" method of "merely supplying sufficient air to do the job" has been condemned. Thus again, although it is claimed that resistance switching effects a reduction in air consumption, aerodynamic considerations may result in an increase in air consumption to obtain the optimum results with a given design.

It would appear, therefore, that the real advantage of resistance switching at the high voltages is the universality of application of the circuit-breaker. If, however, as shown by Messrs. Harle and Wild, circuit-breakers without resistance switching have characteristic curves well above corresponding curves representing the severity conditions of supply systems, I doubt very much whether the addition of the resistance, with its attendant hazards, is economically or practically justified at the higher voltages.

Mr. G. W. Carter: My remarks relate to Messrs. Cox and Wilcox's paper. In the circuit at the top right-hand corner of Fig. 1, the conditions to be satisfied by the resistor are these: (*a*) it must be small enough to reduce the restriking voltage severity of the circuit materially for the first break, and (*b*) it must be large enough to reduce the current materially for the second break. The fact that these aims are simultaneously attainable is due to the very large disparity between the power frequency and the natural frequency of the circuit. To assess the effectiveness of a given resistance in satisfying condition (*a*), some criterion of severity is necessary; a simple and very easily calculable one is the crest voltage in a current chopping condition, though others are possible. In Section 4, the authors point out that in the absence of any damping the value of that voltage is $\sqrt{(L/C)}$ times the current which is chopped. If a resistance with negligible inductance is feasible, and the so-called critical value, $\frac{1}{2}\sqrt{(L/C)}$ is used, the voltage is reduced to 37% of $I\sqrt{(L/C)}$. To get down to 22%, half the critical resistance must be taken, and to get down to 12%, a quarter of it.

In designing such a resistor, it is essential to know how much inductance is permissible in it; here it is of interest to note that critical damping is impossible if the inductance in the resistor is greater than one-eighth, 12½%, of the inductance in the rest of the circuit. But it requires only a very simple argument to show that if the inductance of the resistor is as high as 12½%, no resistance value that we can choose will enable us to get the voltage

below 33% of the undamped figure, which is a very modest reduction. To reduce the severity still further the inductance of the resistor must be made much smaller.

Dr. E. Billig: There is a definite need to test circuit-breakers with low capacitive and inductive currents, such as any breaker might be called upon to handle when disconnecting an unloaded feeder or transformer. Voltage surges have often been reported in the past, the origin of which has not been definitely located, and which have somewhat vaguely been ascribed to "lightning."

The phenomenon of current chopping occurs in several fields of electrical engineering, whenever there is an arc in operation with the current falling to zero. In circuit-breaker operation a simple explanation of current chopping can be given (Fig. C).

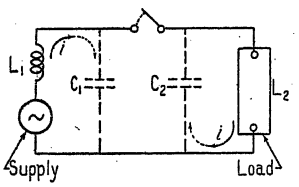


Fig. C

Current is supplied from the system to the load through the system reactance L_1. On opening the breaker an arc is drawn across its contacts which, as explained in the paper, becomes unstable just before passing through its natural zero. The sudden collapse of the current i in the reactance L_1 would induce a very high voltage in it, but fortunately the current through the inductance can be maintained even after the switch has finally opened the main circuit, as it may return as a displacement current via the shunt capacitance C_1 of that part of the system which remains connected to the supply, thus starting an oscillation between L_1 and C_1. The maximum voltage V to which the system may be charged arises when the whole energy stored in the inductance at the instant of current chopping, $L_1 i^2/2$, has been transferred into the shunt capacitance as electric energy, $C_1 V^2/2$. Hence $V = i\sqrt{(L_1/C_1)}$. This is the formula given in Section 4 of the paper. The statement that "the voltage varies directly as the current" is likely to be misunderstood; current and voltage are 90° out of phase, and the relationship given only applies to the crest values of current and voltage, and not to their instantaneous values, as for example in waves travelling on a transmission line.

When the *load* involves a large reactance L_2, e.g. an open-circuited transformer, then again the current in that reactance cannot be broken suddenly, but will charge whatever shunt capacitance C_2 there is available across the load. Any surges thus created will not affect the *supply* side. The two oscillating circuits being bridged by the breaker, the voltage across it will be equal to the difference of the voltages induced in each inductance. Its magnitude depends not only on the circuit constants, but also on the characteristics of the arc path.

Regarding the magnitude of the chopped current, I have found by long experience with arc rectifiers, fuses and breakers, that an arc becomes unstable when the current through it has dropped to about 3 to 5 amp. For the tests recorded on pages 490 and 491, the value of the chopped current could easily be determined by dividing the voltage immediately before chopping by the ohmic value of the arc-shunting resistance. As this value is not given in the paper it had to be found from a close examination of the oscillograph records given. In view of the small scale, however, it would be more satisfactory if the authors could state the value of the resistance used in these tests. As a result the critical current seemed to come approximately to the same value of about 4 amp in all five records on page 491.

It is interesting that arcs under such widely different conditions as obtain in oil or air-blast circuit-breakers, in cartridge fuses and in mercury-arc rectifiers, should all become unstable at about the same value of current. This seems to point to some fundamental feature in the mechanism of arcs generally. Applied to the generation of surges, such a result would be useful as it would enable one to predict their magnitudes by multiplying the chopped current by the surge impedance of the system in question. Mr. Cliff's figures for surges of 25 and 60 kV observed behind a transformer and a reactor respectively, seem to agree well with the surge impedance of 5 000 ohms usual for transformers and several times that figure for air-cored reactors.

Mr. D. F. Amer: My comments are confined to the paper presented by Messrs. Cox and Wilcox.

The air consumption of outdoor air-blast circuit-breakers affects the capital cost of the circuit-breaker only, and has little or no bearing on the maintenance cost. In the 132-kV design shown, any economy in pipe sizes, valves, reservoirs, etc., resulting from the reduction in air consumption, is in my opinion completely nullified by the addition of another switch-head, the resistance and the duplication of valves.

Two resistance-switching arrangements are referred to, and it appears that a change in technique for service at 66 kV and above is necessitated by the low insulation limit which is inherent in the simpler 33-kV arrangement. Can the authors state whether this is correct?

The design of the resistance is based upon a compromise between its thermal capacity and the minimum natural frequency to be controlled. In this respect are these arrangements to be tested at the more usual lower natural frequency to make sure of the breaking capacity? Is the resistance always switched in at the low natural frequency encountered in service? At 132 kV these values are certainly less than 1 000 c/s and the voltage across the shunted head is determined by the degree of damping of the lowest natural frequency. At 220 kV these problems would be accentuated, and I should like to ask the authors if they propose to use resistances at this voltage.

With regard to over-voltages caused by the action of the circuit-breaker, I do not agree that impulse tests across the gaps will form a reliable indication of the maximum suppression peak voltage. The presence of ionized gases from the initial metallic arc and the subsequent capacitance discharge currents, as indicated by the multiple restriking in Fig. 3, considerably reduce the dielectric strength of the circuit-interrupting gaps. Tests indicate that this is of the order of 50%. The prevention of serious over-voltages due to switching the charging currents of long lines can only be determined in the testing station in a negative way; that is, the circuit-breaker must not allow any restriking when interrupting a capacitive loading. No harmful over-voltages can then occur. In this respect the design shown does not differ from a circuit-breaker not fitted with resistances.

Mr. A. M. Cassie: Messrs. Harle and Wild advocate the use of the R.R.R.V. in taking account of circuit severity. If we accept this criterion, their treatment of restriking voltage in relation to circuits in service and in testing stations leaves little more to be said. There is still, however, the question whether the R.R.R.V. is the best, or even an adequate, method of reckoning severity.

I should like to refer to the alternative method which the authors mention, namely the severity factor deduced from the energy-balance theory. This is, of course, as much an over-simplification as the R.R.R.V., but even if, at the present time, this formula must be regarded as merely another empirical means of relating circuit-breaker performance with circuit conditions, it is in no worse position than the R.R.R.V. In choosing between the two methods two tests can be applied. First, which gives

the more consistent results when applied over as wide a range as possible? For example, if in Fig. 6 of their paper, the energy-balance severity factor had been used in place of the R.R.R.V., would a unique curve still be obtained? Secondly, if there is nothing to choose between the two methods in respect of consistency, the choice would then be governed by the relative simplicity in application. In both these respects it would appear that the energy-balance factor has some advantages.

There are, naturally, insufficient data in the paper to use the authors' results for re-drawing Fig. 6 employing the energy-balance factor. Similar results obtained by the E.R.A. suggest that the test of consistency certainly holds when the energy-balance factor is used. Nor does it lead to difficulties of the kind revealed by the discontinuities which occur in the 6·6-kV and 11-kV curves of Fig. 11A. Such discontinuities are presumably due to the presence of two frequencies of approximately equal amplitude and would certainly not correspond to discontinuities in switch performance.

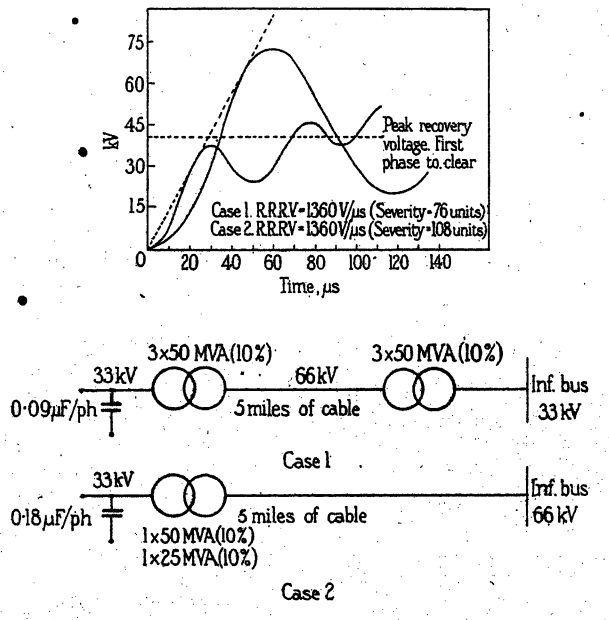


Fig. D

Fig. D shows another case where the two methods give different answers. The restriking voltage, as specified by the authors, gives the same severity for the two circuits shown, whereas the energy-balance factor gives relative values of 78 and 108. The details attached suggest that Case 2 would be more severe than Case 1.

Applying the second test, the energy-balance factor is the result of a simple arithmetical operation, whereas the R.R.R.V. involves drawing curves and tangents. The convention adopted in drawing these tangents might very well depend on the type of switch under consideration. The energy-balance factor suffers from the same disadvantage, namely that it is not a function of the circuit parameters alone. It may be that this difficulty is inherent in the problem and that it is impossible to avoid it.

Mr. A. Allan: I fully support the advocacy of multi-breaks as a means of proving breaking capacities beyond the normal scope of testing stations. Unit testing is readily applicable to air-blast breakers which are divisible into units with similar performances. Given this, by proving the breaking capacity of the most highly-stressed unit and the ratio of the performance of one unit to that of the complete assembly, the breaking capacity of the whole switch can be deduced.

The subdivision of a high-voltage circuit-breaker into a number of units effects a corresponding reduction in both the amplitude and the R.R.R.V. at each nozzle. Thus the problem of dealing with high R.R.R.V.'s is solved, and it remains only to limit the peak voltage across each break. This can be done without departing from the optimum relationship of gap and nozzle diameter, by providing safety gaps suitably disposed.

As an alternative to the elaboration of resistance switching, Fig. E shows the general arrangement of a 132-kV air-blast

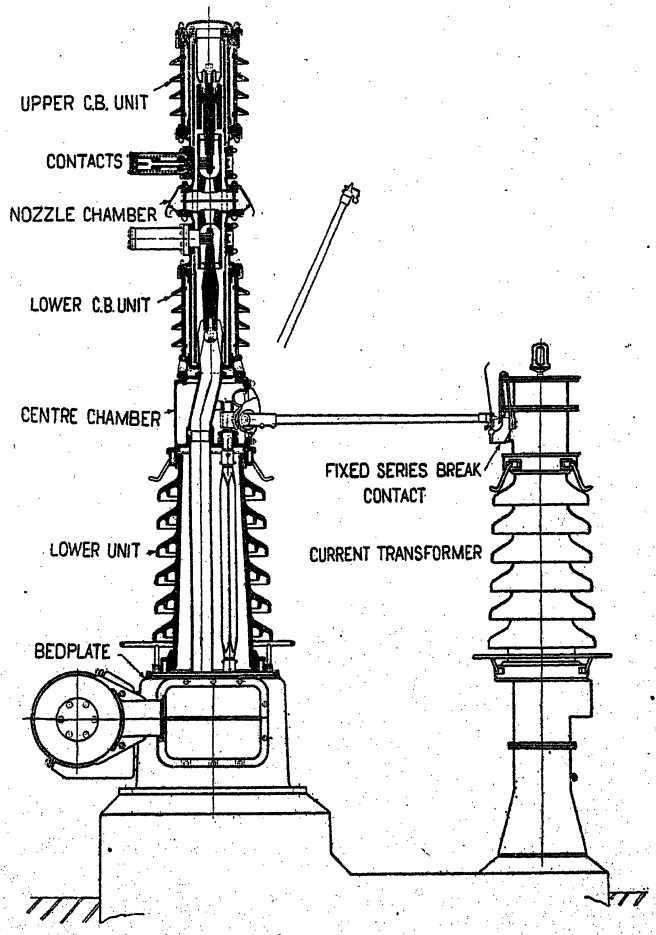


Fig. E

switch having a rating of 3 000 MVA. It comprises simply two single-nozzle circuit-breaker units, a current-transformer unit, and the customary series air-break switch. The air stream, flowing upwards from the blast-valve at the base, divides into two streams feeding the upper and lower nozzles. The two arcing chambers are identical in construction, and the aerodynamic design of the passages is such that the rate and amplitude of pressure rise in these chambers is the same. 55% of the voltage is distributed across one break, and due allowance is made for this in unit testing. This breaker has been tested, single-phase, up to 3 200 amp at 114-kV recovery voltage, and 14 000 amp at 38-kV recovery voltage, on half the switch: the maximum arc duration is 3 half-cycles, and the air consumption of the three-phase breaker is 135 ft^3 of free air per make-break operation.

Tests made on a four-nozzle 132-kV breaker of similar design indicate that greater economy in air consumption can be achieved thereby, but the additional complication involved is of questionable value as at this voltage the consumption of the breaker is

not necessarily the deciding factor in the size of the air-compressor equipment, since this may be determined rather by the volume of air required for insulation maintenance.

Mr. L. H. Black (*communicated*): The introduction of the air-blast circuit-breaker and the resulting prominence given to circuit severity seem to necessitate a more precise definition of the rate of rise of restriking voltage. Messrs. Harle and Wild mention that commonly used, namely (to give the definition rather more completely) "the slope of the steepest tangent touching the restriking voltage curve and passing through the origin." This definition is usually adequate for single-frequency circuits, but may need qualification for multi-frequency circuits. In these circuits the restriking transient often contains component voltages of high frequency, but of small amplitude; such components, though they produce a high initial rate of rise, are relatively innocuous because of their low amplitude. It may therefore be advisable to ignore certain of the higher-frequency components when assessing the circuit severity. The authors presumably had this in mind during the preparation of Fig. 11A, when they ignored the preliminary peaks having amplitudes below 80%.

It would be interesting to hear what considerations led them to decide on this particular percentage, and whether they regard it as a suitable one to form the basis of a more exact definition of the rate of rise.

If the 80% criterion were applied to the case discussed below, it would give a figure for circuit severity only one-fourteenth of that based on the initial rate of rise—which is mainly due to a high-frequency component of about 20%. Would the authors consider it advisable to neglect the effect of this relatively large component during the interval before a total amplitude of 80% was attained?

In the actual case mentioned above, the plant consisted of a generator with earthed neutral supplying a step-up transformer via a 22-kV cable network, the transformer secondary being open-circuited. A 3-phase fault clear of earth at the transformer secondary terminals is assumed, and the following results are calculated for the first phase to clear: (*a*) initial R.R.R.V. due to 20·8% high-frequency component, 1350 V/μs; (*b*) R.R.R.V. based on tangent to first peak to exceed 80% of recovery voltage peak, 93 V/μs.

The calculation was repeated for the second (and final) break, which was assumed to occur simultaneously on the remaining two phases. The results were: (*c*) initial R.R.R.V. due to 18·8% high-frequency component, 1730 V/μs; (*d*) R.R.R.V. based on tangent to first peak to exceed 80% of recovery voltage peak, 135 V/μs. The above conditions occurred simultaneously at both of the final breaks.

In this particular instance, the R.R.R.V. at the final break is therefore appreciably greater than at the first break. Do the authors consider that the implications of this result might be realized in practice, and have they any test results indicating restriking on the remaining two phases after the final opening of the first phase? The air-blast circuit breaker, being more affected by the R.R.R.V., might perhaps produce this condition, but its occurrence in an oil circuit-breaker would be unlikely. If such a condition were possible it would be necessary to modify the calculation of the circuit severity accordingly.

Mr. C. E. R. Bruce (*communicated*): Regarding the rating of circuit-breakers, one aspect of the relation between single- and three-phase testing, and of each to the worst fault conditions, has seldom been mentioned.* It is one in which the advantage lies distinctly with the gas-blast as opposed to the oil circuit-breaker, since the former shows greater regularity of operation, and for the most part is developed and tested as a single-phase unit.

In a three-phase test, the voltage ruptured in the first phase to clear is 1·5 times phase voltage, but such a test is practically equivalent to making three single-phase tests at this voltage and selecting the shortest, the selection being made automatically by the circuit-breaker. In order to ensure, therefore, that the worst possible conditions of energy liberation have been met with in one phase of a three-phase test, the voltage would have to be increased by a factor to cover this easing by selection, one which will vary according to the type of breaker tested.

Although the variation in repeat tests in the gas-blast circuit-breaker is small, nevertheless Dr. Whitney showed that there may be considerable variation in the energy liberated within the range of one current loop. Now, in a three-phase test a zero passage usually occurs within about 60° from the start of arcing, whereas in a phase-phase test, and also in the fault conditions mentioned below, this first zero passage may occur only after a complete half-cycle or more in an asymmetrical test, so that here, too, the successful rupture of a three-phase short-circuit does not establish the breaker's capacity to rupture the arc under all conditions.

The fault conditions referred to above are those either between two phases and earth in a system having high neutral impedances,* or one across two phases when load current continues to flow in the third phase of a system with isolated neutral point. Under these conditions one pole has to break practically line voltage, as in a phase-phase test applied to only one pole of the breaker, and has therefore to break a voltage 15% greater than that ruptured in the first phase to clear of a three-phase test.

Mr. J. R. Mortlock (*communicated*): Having read both papers and listened to the discussion it appears that: (*a*) some perturbation exists among the designers of air-blast breakers on the score of restriking voltage severity; (*b*) there is no agreement yet in the validity of either of the two methods—energy balance or rate of rise—of assessing the severity; and (*c*) the determination of the restriking voltage transient by calculation cannot be more accurate than the assumptions made in assessing the circuit parameters; the more accurate the equivalent circuits used, the more laborious the evaluation. If simplified circuits are used, then some doubt must always exist as to the validity of the result.

It is possible that when the method of assessment has been established beyond controversy and ample test data on the natural restriking transients of installations are available, severity factors, actually easements, may be agreed upon, but until then the logical outcome is to design breakers which are independent of natural restriking transients.

In effect, the breaker is made independent of its location on any system, and of any arrangements of the system. Equally, the use of a breaker at any location must not introduce additional hazards to the system. Current suppression effects are now well known and recognized: their control can be but an advantage, and the paper by Messrs. Cox and Wilcox marks a notable step forward in this direction.

Mr. J. J. O'Doherty (*communicated*): The curves in Fig. 10 of the paper by Messrs. Harle and Wild are of considerable interest to users of circuit-breakers. Would the authors say if these curves include: (*a*) the effect of the magnetic energy of transformers in so far as this acts as an equivalent shunt resistance, or (*b*) the effect of commercial load?

[The authors' replies to the above discussion will be found on pages 506 and 507.]

* BRUCE, C. E. R.: *Journal I.E.E.*, 1940, 87, p. 16.

* BIERMANNS, J.: "Hochleistungschalter ohne Öl," *E.T.Z.*, 1930, 51, p. 299.

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 3RD APRIL, 1944

Mr. A. R. Blandford: Whilst it is true that the behaviour of air-blast breakers is influenced more than oil breakers by R.R.R.V., it is important this feature be allocated to its proper place and not used as a reason for: (*a*) introducing complicated methods of determining the required service rating; (*b*) imposing unnecessary test severity; and (*c*) introducing what I would call "quality grading," which is most undesirable.

The maximum R.R.R.V. for any circuit-breaker location in a network can be easily predicted, and whether the breaker is of the air-blast or oil type, it can be readily arranged to meet the most severe conditions. Consideration of individual breakers is obviously undesirable, as these might during their life be transferred to other parts of the system. Messrs. Harle and Wild advance suggestions for the standardization of air-blast circuit-breakers, and an interesting theory which, while not agreeing with the characteristic curves produced for the rate of recovery of the electric strength of an air-blast circuit-breaker, could usefully form the basis for further consideration.

There is need for a general survey of the circuit characteristics throughout the country, and the data published by the authors and others are not yet sufficiently comprehensive to enable switchgear authorities to determine the necessary standards in order to relieve the purchaser from having to concern himself with details beyond those at present specified for oil circuit-breakers.

In speaking on this paper in London, I referred to Fig. 4(*c*), curves 1 and 2, which I concluded had been produced for the sole purpose of showing the expected relationship of the R.R.R.V. at 10% and 100% duty cycles. I now understand that they are also intended to indicate actual values of R.R.R.V. at which an air-blast circuit-breaker might be expected to give satisfactory performance. If this is correct, then the authors' figures are widely different from test results obtained on other designs.

It is gratifying to see the authors have developed a new definition for the R.R.R.V., which definition I criticized in my recent paper. Presumably they still refer to this characteristic as a "restriking voltage" to comply with the existing B.S. nomenclature. Actually, it is not a restriking voltage at arc extinction, but is the transient of the recovery voltage and, as such, should be defined as the R.R. Recovery V. The oscillograms shown on the screen indicate that it forms part of the same trace as the normal frequency, which is, therefore, one with the normal transient voltage.

In Section 4.3, the statement that resistance switching is practically essential for heavy-duty lower-voltage breakers, should, I think, be qualified by "lower-voltage breakers of the axial-blast type," as all types of air-blast circuit-breakers do not necessarily possess the same characteristics in this respect.

Messrs. Cox and Wilcox in putting forward a design of air-blast circuit-breaker for 132 kV, 2 500 MVA, are, I believe, the first to consider resistance switching to be necessary at this voltage and rating. Air-blast circuit-breakers for these high-voltages and ratings have been in service on the Continent for some 15 years, and in America for 2 years; while in this country 33-kV breakers have been in service for 5 years, and 66-kV breakers for 2 years, all without resistance switching. At these voltages the natural frequencies are generally very much reduced, and whilst agreeing with the authors that resistance switching will damp peak over-voltages, test and experience have proved that it is quite possible, without undue stressing of the system insulation, to provide satisfactory, safe, and economic air-blast circuit-breakers without resistors for 66 and 132 kV. The authors state resistors also serve the purpose of improving the rating of the circuit-breakers. This is quite true, but as it is possible with an air consumption comparable with that used by the authors to achieve satisfactory design, the complication would seem to be quite unnecessary.

Mr. K. J. R. Wilkinson: The definition of restriking voltage suggested by Messrs. Harle and Wild applies only to the limiting case of zero power factor, and it does not readily permit the defined characteristic to be measured. For these reasons I would submit the following amended definition: "The inherent restriking voltage of a circuit is that voltage transient which would appear between the contacts of a circuit-breaker, if stated current were instantaneously interrupted by it at current zero, in such manner that prior to interruption the arc offered zero impedance and after interruption, infinite impedance. This voltage transient may be taken as equal in time scale, and everywhere proportional in amplitude, to that which would be contributed at the open breaker by injecting into the system a sine wave of current at power frequency, starting at a current zero."

In calculating the R.R.R.V. for cables (Section 11.2.1), the multiplication of $1{\cdot}5Z$ by di/dt is appropriate only if no reflections occur, and it is advisable to compare this result with that obtained by assuming an equivalent lumped capacitance for the cables. Fig. F shows the calculated form of the first two reflections within

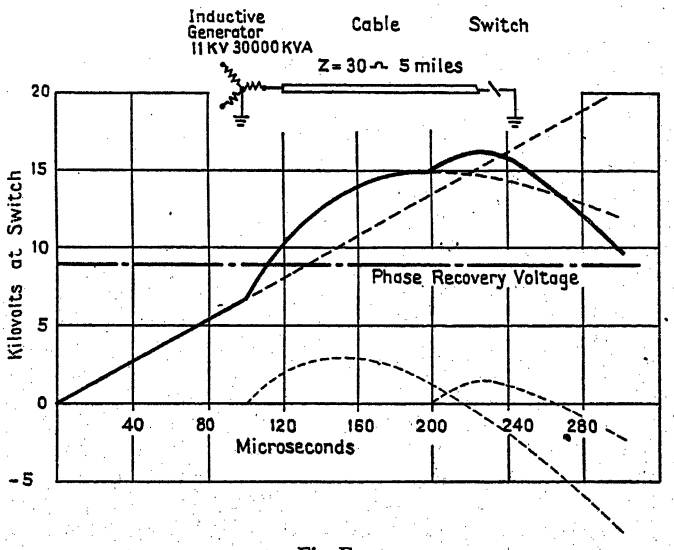


Fig. F

5 miles of cable, when a single-phase fault is interrupted; this illustrates the mechanism by which a cable "transforms" into a capacitor.

Employing a resistor, Messrs. Cox and Wilcox encourage the air-blast breaker itself to limit possible over-voltages during interruption. The practical desirability of a fixed resistor might appear to conflict with the need to serve wide ranges of system impedance, but this is largely compensated by the tendency for over-voltages to occur at light currents by chopping; by its nature, this involves only the more local system quantities and so demands a proportionately limited resistance range.

Fig. 3 of the paper is said to illustrate current chopping, but I feel it is more likely that the current—here formed of discontinuous sparks probably reaching some hundreds of amperes—extinguishes each time naturally by the discharge of a local capacitor, and this effect should therefore be distinguished from current of normal amplitude chopped by switch action. Fig. 3 more appropriately demonstrates "voltage chopping."

"Surge impedance" has a definite meaning when applied to transmission lines or cables, but its application as in Section 4,

to $\sqrt{(L/C)}$ is to be deprecated. The impedance to transients of an L-C circuit is essentially variable with time; the surge impedance of a cable is constant. I have suggested* the impedance most relevant to current chopping phenomena be termed "crest impedance," a circuit being said to have Z ohms crest, in which Z volts crest appeared per unit-function ampere suppressed.

Mr. L. Gosland: A standard method of calculating the effect of opening a given circuit is to consider the effect of applying to the system, between the circuit-breaker terminals, a current equal and opposite to that which would have flowed had the circuit not opened. Such a method defines the duty of a circuit-breaker in terms of a current and an impedance. In oil circuit-breakers only the power-frequency impedance need be considered; for air-blast breakers, the higher-frequency characteristics of the circuit have also to be taken into account, and the duty of such a circuit-breaker may be defined by stating the current it has to handle and two impedances, one the power-frequency impedance, and another related to the high-frequency characteristics of the network in which the circuit breaker is to operate.

Provided the values obtained are properly interpreted and no inconsistencies arise, the precise manner in which a magnitude is assigned to the high-frequency impedance is immaterial. For example, the rates of rise of voltage used by Messrs. Harle and Wild may be translated into recovery impedances of so many ohms.† The use of the rate of rise of voltage, or any quantity depending directly upon it, as a measure of circuit severity, leads however to inconsistencies; and in this respect considerable advantage would be gained by translating the rates of rise of voltage used by these authors, into severity impedances defined by the energy equilibrium theory to which they refer in Section 3.2.

The effects of using resistance switching on the net circuit severity that the shunted head of the breaker has to deal with, can be assessed by considering the effects of the resistance connected in parallel with the severity impedance of the circuit: and a little consideration shows that, even if resistance switching is adopted, the severity of the testing circuit cannot be neglected completely. A degree of freedom is, however, conferred on testing authorities by the possibility of testing the shunted head with increased parallel resistance to compensate for any deficiency in the inherent severity of the test circuit.

The authors of both papers refer to the testing of single units which incorporate multiple series breaks. There is little doubt that, with parallel resistance of the order used by Messrs. Cox and Wilcox, the method they suggest is entirely adequate. When no parallel resistance is used, the method suggested by Messrs. Harle and Wilde appears to be a sound approach to the problem. Consideration should, however, be given to measuring the voltage distribution between breaks, on which the performance ratio is based, by means of tests at reduced voltage and full current, as well as at reduced current and full voltage as suggested. The magnitude of post-arc conductivity may well increase by 10 or 100 times over the range of extrapolation implied, and it should be given the chance of showing its worst effects by tests at full current. Capacitive impedances determining voltage distribution between breaks are likely to be of the order of 10^4 ohms per break at the frequencies of the transients concerned. Post-arc conductivity may well give impedances considerably higher than this, so that there is a fair chance that capacitance effects predominate, and that the method suggested is perfectly adequate. This is a point which could probably be decided by experiment.

Dr. W. G. Thompson: Experiments carried out in connection with the Marx rectifier using electrode arrangements similar to those shown in Messrs. Cox and Wilcox's paper, have indicated the importance of proper design of the exhaust chambers in reducing the arc length and the excess heat generated. A long arc loop has a tendency to short-circuit itself in the looped portion and produce fluctuations in the total arc voltage, and while an arc may have all the appearance of being stable between the electrodes, the portions concealed in the exhaust system may be very ragged, and tend to produce conditions unfavourable to arc extinction by choking the air flow. Have the authors come to any conclusions on the relative influence of the total arc voltage, and the arc volts per cm in producing surges at arc extinction? The authors attribute the position of the breakdown of the electrode gap to variations in air density due to flow conditions, but I suggest that the sharp edges of the electrodes are also significant in this connection.

With regard to impulse testing of electrode gaps, I have found that the impulse voltage required for certain breakdown is about 20% in excess of the minimum breakdown voltage for the gap. Since the surges produced by the extinction of the main arc are oscillatory, has a high-frequency testing voltage been considered as a possible alternative for testing the gap? Mention might be made of enhanced breakdown voltage produced by oil vapour from the compressed air.

In Messrs. Harle and Wild's paper, two dielectric recovery theories are mentioned. I suggest that the difference between the two is more apparent than real. My experience with rectifiers of the air-arc type has been that there is a practically instantaneous recovery of the dielectric strength of the electrode gap up to 30%, and recovery to 80% follows within about 50 μs.

Mr. J. Christie: In the paper by Messrs. Cox and Wilcox, I question the need for resistance switching at voltages above 33 kV, and consider that multi-breaks, with suitable voltage limiting gaps, are as effective as resistors in preventing over-voltages. Unfortunately, at the lower voltages (11 and 33 kV) the gaps are so very small, and the duplication of breaks so expensive, that resistance switching is preferred.

At the higher voltages, using a convenient air pressure of, say, 250 lb/in^2, each break has a definite voltage limit. This necessitates at least two breaks for 132 kV. These breaks, if correctly designed, are of such dimensions that a consistent breakdown is obtained, thus preventing serious over-voltages. With multi-breaks it is possible to obtain satisfactory operation up to 3 000 MVA at 132 kV, without producing abnormal over-voltages, even when clearing magnetizing or charging currents. Therefore I find it difficult to understand why the authors have adopted resistance switching at this voltage with all its complication and duplication. Theoretically, the authors have made out a good case for resistance switching, but from a practical point of view there is no evidence that it is necessary at the higher voltages at which the complications introduced by the use of resistors cannot, in my opinion, be justified.

Provided it is reasonable, the air consumption is not important, as the amount of air used for the actual arc-quenching operation is small compared with that required for air conditioning, and that lost through leakage.

I agree with the authors as regards part-testing of circuit-breakers. With the non-resistor type this is only possible if the breaks are mechanically, electrically, and aerodynamically similar.

It would be interesting to know what routine test the authors propose to adopt in service for checking that the resistor is sound; what duty cycle the resistor will withstand; and what interval of time is necessary for cooling.

Mr. C. J. O. Garrard: It is apparent from the papers and from the discussion that in adopting air-blast breakers rather than oil breakers we must reckon with many new problems which have

* "Recurrent Surge Oscillographs, and their Application to Short-time Transient Phenomena," *Journal I.E.E.*, 1938, 83, p. 670.

† Boehne, E. W.: "The Determination of Circuit Recovery Rates," *Electrical Engineering*, 1935, 54, p. 530.

not troubled us hitherto. What do we expect in return? Let us compare the two types.

Regarding breaking capacity, service under onerous system-severity conditions, speed of operation, simplicity, size and cost, there is either no difference or the advantage is on the side of the oil circuit-breaker. From the point of general reliability and ease of maintenance, it is unlikely that the air-blast breaker will show any striking advantage, except perhaps for certain special applications. There remains the question of fire-risk, on which it may be observed that extremely few switchgear fires have been due to oil in circuit-breakers, as distinct from oil or compound in other parts of the gear. I make this comparison because I think that our policy should not be influenced by exaggerated ideas of the benefits to be obtained, at not inconsiderable trouble and expense, by abandoning a type of breaker that has given good service for many years. Yielding to fashion is as harmful in one way as is undue rigidity in another.

The circumstances attending the use of circuit-breakers make it necessary to draw up a specification for air-blast circuit-breakers at a time when the development of the art is scarcely far enough advanced. It is therefore all the more important to guard against an excessively severe or complicated specification. Suggestions such as those of Messrs. Cox and Wilcox should be resisted, based as they are upon experience of current chopping with one particular design of breaker, in a circuit whose impedance consists almost wholly of lumped air-cored inductance, such as rarely occurs in practice. The proposals of Messrs. Harle and Wild for standard minimum rates of rise of restriking voltage appear to me to be too high.

In drawing up our specification we should not be blind to the obvious fact that, on the Continent and all over the world, many thousands of air-blast breakers are giving excellent service, although they would not pass the tests suggested by the authors, but have been designed and rated on the basis more of service experience and site tests than of station tests.

I would like Messrs. Harle and Wild to explain more fully their idea of "performance ratio." So far as I can see, their expression for P_n towards the end of Section 11.3.2, by substitution of previous expressions reduces, for example, to the statement: $P_n = I_4 U_4$ where $n = 4$. This simply means that the "performance" of the breaker is equal to the product of an arbitrary current (I_4) and the maximum R.R.R.V. (U_4) which can be obtained in the test plant in conjunction with this current. Any usefulness that this statement may have depends upon $I_4 U_4$ remaining constant over a wide range of I_4; to prove that this is the case involves us in testing the breaker according to present orthodox methods.

Mr. J. Grant: In their paper Messrs. Cox and Wilcox have correctly shown that there are two independent problems to be solved in the design of high-voltage air-blast circuit-breakers: (1) interruption of the full breaking capacity, and (2) suppression of over-voltages. These two requirements, however, are so entirely different that the provision of two similar interrupters for the two purposes would appear to be uneconomic, both in material and in the space occupied.

Two methods of resistance switching are shown in the circuits of Fig. 8. It is stated that method (*b*), in which the same air blast is employed in both main and resistance gaps, is most suitable up to 33-kV. No reason however is given for this demarcation. Method (*b*) depends for consistent operation upon ionization carried over from the main to the resistance gap; it is thus effective where high currents have to be broken whatever the recovery voltage. The over-ruling disadvantage of method (*a*) is that an independent blast and interrupter are required, as, for instance, in the authors' design. It is therefore my belief that the upper MVA ranges, for which interrupters without resistance control become uneconomic, will be best dealt with by single-blast resistance interrupters and that their rating of 2 500 MVA at 132 kV will prove no exception to this rule.

Mr. J. S. Cliff: Unit testing is one of the artifices which can be adopted for testing air-blast circuit-breakers above the maximum output of the test plant. It is reliable provided precautions are taken to ensure that the voltage distribution across the breaks is accurately measured and controlled. Messrs. Harle and Wild propose to measure this by means of the cathode-ray oscillograph. The voltage distribution is controlled by the capacitance between the contacts and the parallel capacitance to earth. These have very small values; hence if an oscillograph is connected across a break, its capacity will affect the voltage distribution appreciably and give the wrong result, the possible error being large unless complicated corrections are made.

Messrs. Harle and Wild propose by the use of models to obtain the MVA/R.R.R.V. characteristics at values above those obtainable on the test plant. They lay down no laws for the dimensions of these, and in the present state of the art, I think they will find this impossible until very much more work has been done on the electrical and aerodynamic theory of these circuit-breakers. It is clear from what the authors themselves say that many tests are necessary to prove fully an air-blast circuit-breaker, particularly at high MVA ratings. To establish the MVA/R.R.R.V. curve alone will take several dozen tests at least, and since this curve represents the borderline between clearing and failing, the replacements for contacts and arc chamber will be quite appreciable. The few tests specified in B.S.116, or the even shorter series advocated by Messrs. Cox and Wilcox, will be quite inadequate unless backed by considerable development testing. The argument of these authors regarding current chopping by air-blast circuit-breakers would have been much more convincing if they could have proved that air-blast breakers were worse than oil circuit-breakers. That was not possible, so apparently to raise this characteristic to the status of a real bogey they used air-core reactors to imitate the magnetizing current of an iron-core transformer. This is not justified, as, owing to the inductance/time and damping characteristics of a true transformer, the number and magnitude of the high-voltage peaks are reduced to negligible proportions. During 15 years' operation of the Grid, instances of flashover when switching-out transformers have been insignificant and have caused no internal damage. If this were a serious menace it would be preferable to use a protective gap having a closer sparkover range than 150–250 kV as shown in Fig. 6.

I would not accept the authors' rating of 2 500 MVA at 132 kV on the basis of the tests put forward in Table 1. The full 100% symmetrical current of 11·5 kA was interrupted by two breaks at a recovery voltage of only 43 kV, which is equivalent to 38% normal. No asymmetrical test duty is included. The authors rightly recommend unit-testing, and demonstrate that it is essential to base the final results upon the conditions obtaining for the least favourable arc gap. Why has the rating of 2 500 MVA not been substantiated by unit tests?

[The authors' replies to the above discussion will be found on pages 506 and 507.]

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSIONS

Messrs. J. A. Harle and **R. W. Wild** (*in reply*): The discussion has brought out several points which were omitted from the paper owing to space limitations. It has centred on the air-blast breaker, with particular emphasis on the means essential for assessing reliably the severity of any circuit with respect to its influence on breaker performance. The importance of arriving at a satisfactory solution of this problem is fundamental to the industry if progress is to be made and confusion avoided. It is felt that if this aspect can be shorn of unnecessary refinements at least a tentative working basis for standardization will be possible. Suitable tables and charts can be embodied in the appropriate British Standard, if the method proposed for standardization is adopted.

When a circuit has a single-frequency transient characteristic, it is readily assessed for severity and few difficulties arise in relating this severity to the performance of circuit-breakers. Difficulties of assessing circuit severity arise when double-frequency transients or other changes in characteristic result, such as reflections where long lines or cables are involved, which cause initial peaks of relatively low amplitude to be superimposed on a slower rising fundamental which reaches its maximum very much later.

The practical problem of assessing the severity of these complex cases largely disappears if it is dealt with under the two heads of (1) testing stations and (2) systems. The reason for this will be appreciated when it is remembered that: 1(*a*) double-frequency transients on testing-station circuits cover only a very limited range of circuit-breaker ratings. These could be assessed as indicated below. 1(*b*) reflections and other irregularities rarely arise; consequently it can be established by proving tests that a circuit-breaker can deal satisfactorily with a severity of an agreed maximum at its respective duty cycles.

The only remaining problem is then the effective assessment of severities on systems at breaker locations where line reflections may give rise to severities which should be taken into account, in order to ensure that they do not exceed the severity for which the breaker is proved. The following points summarize the general position with respect to procedure for ensuring that all system severities fall within recognized maximum values, which can be readily assessed to permit reliable comparisons to be made: 2(*a*) That severe system switching points, such as series reactors, are effectively controlled on the lines proposed in the paper; and 2(*b*) the presence of cables or overhead lines adjacent to the breaker generally constitutes an easement, but to assess cases up to 8 miles of overhead line and up to 4 miles of cable, the following procedure can be adopted:

(i) *Overhead Lines:* The rate of rise obtained from the main oscillation (i.e. ignoring any reflections) given by the inductance of the circuit oscillating with the total capacitance, tends to be low for the lower voltage circuits (below 33 kV). This is because an initial linear rise due to the surge impedance is not taken into account. An amount could be added to the rate of rise obtained for the main oscillation giving a resultant rate of rise as follows:

Resultant rate of rise =

$$\left[RRV_m + x\left(1{\cdot}5Z\frac{di}{dt} - RRV_m\right)\right]$$

where RRV_m = rate of rise of main oscillation

$$x = \left(1{\cdot}5Z\frac{di}{dt}\right)\frac{2l}{v}\Big/2E,$$

Z = surge impedance of cable or line,
l = length of cable or line,
v = velocity of propagation of electric waves on cable or line, i.e. 985 ft/μs for overhead lines, and 300 to 600 ft/μs for cables,
$E = (1{\cdot}5 \times 1{\cdot}414 \times$ rated voltage$)/\sqrt{3}$, and
i = short-circuit current in the cable or line.

(ii) *Cables:* The severity for cables is much less than for overhead lines, but the above treatment is applicable for cable lengths up to 4 miles. When the initial peak due to the first reflection is attained in no more than 10 microseconds it can be ignored.

If the procedure proposed in the paper for determining circuit severity is supplemented on the lines given above, satisfactory comparisons of the severity for particular breaker locations on any system with the circuit-breaker test data can readily be made with a satisfactory accuracy.

Replies on specific points raised by individual speakers are given below.

Mr. Marshall: The authors are gratified to note that the three advantages gained by including relatively short lengths of cable justify the adoption of this method of severity control in cases likely to prove abnormal.

Mr. Blandford: Mr. Blandford doubts the wisdom of our generalization that air-blast circuit-breakers without resistances have a characteristic limiting condition which conforms to that of a rectangular hyperbola. Our researches on different types of air-blast circuit-breakers are confirmed by the published data of other experimenters which indicate that this law holds for both the cross-blast and axial-blast types. The rate-of-rise values quoted by Mr. Blandford give no indication as to whether they represent limiting conditions of performance; consequently, they are difficult to assess, as it is only by determining the limiting conditions of rate of rise at the rated voltage for the percentage duty that gives such figures any real significance.

That half a column devoted to plain-break circuit-breakers should be considered too generous is not supported by the position these breakers still hold in the industry.

Fig. 4 shows the relative performance of the three different types of circuit-breakers operating on the same duty cycles and circuit severity. The air-blast figures represent the performance for a low nozzle pressure and small nozzle diameter selected in order to permit the limiting conditions to be reached within the test-circuit severity available. The curves typify the general characteristics, but are not intended to represent production types generally as regards performance. This should be clear from Fig. 10 and Section 11.3.

Mr. Blandford's second impressions are generally more favourable, although still cautious, on the question of our proposed standardization for proving air-blast breakers. We partly agree with his comments on certain heavy-duty lower-voltage breakers, as these types were in our mind at the time, but we consider that for air-blast designs it is a question of the performance standard required and of economic considerations.

Dr. Whitney: We agree that it is important, when assessing performance, that a complete loop of arcing should be obtained after the contacts are fully separated; and would stress that arcing in excess of one complete loop does not necessarily mean that the circuit-breaker is about to fail.

Mr. Flurscheim: The only objection to using a material having a bent voltage/current characteristic is the fact that, although the initial transient voltage amplitude is reduced, the actual rate of rise is very little influenced; this is a very important point as it is the initial slope which determines a restrike when the amplitude exceeds a certain minimum. This is clearly demonstrated in the oscillograms of Fig. 8; otherwise, the adoption of such a resistance which was primarily developed for dealing with

transient voltages is rather attractive. Confirmation is given by Mr. Flurscheim that the influence of rate of rise on performance depends upon the design and on the restriking-voltage waveform. This is tantamount to approval in principle, leaving the question of interpretation of severity to some agreed standard method.

Mr. McNeill: The question of double frequencies had, like other aspects of the subject, to be somewhat summarily dismissed owing to space restrictions. If the service conditions are carefully considered it will be seen that the actual range of gear likely to be influenced by double-frequency transients is very limited, and as suggested should present little difficulty if considered by the authorities with a view to standardization. While we contend that the 80% minimum initial peak offers a simple and satisfactory assessment, it lacks precision in that it causes discontinuity in station and system characteristic curves.

As testing-station circuits usually change progressively as regards rate of rise when carrying out proving tests for a given machine connection, it might be preferable to assess severity by using a rate of rise deduced from an equivalent frequency corrected for damping. This frequency could be determined from: $f_e = [0{\cdot}01ad_hf_h]/[1 + (20/a)^3] + [0{\cdot}01bd_lf_l]/[1 + (20/b)^3]$ where f_h, f_l are the high and low frequencies; d_h, d_l the damping factors; and a, b the percentage amplitudes.

The rate of rise would then be given by $U = 4{\cdot}55 \times E \times f_e$, where E is the 50-c/s peak recovery voltage. This would avoid any discontinuity in the rate-of-rise characteristic (for a circuit in which the series reactance is the only variable), which results if peaks below a given amplitude are ignored, and eliminates any possible difficulty in obtaining agreement on the minimum initial peak to be ignored at the cost of a little more complication.

The performance factor can only be determined for any multi-break circuit-breaker by many tests in the vicinity of failure for each stage of a cascade arrangement. The falling-off in the performance ratio with increasing stages of cascading is to be expected from a purely physical aspect and is due to: (*a*) the progressive falling-off in voltage distribution with increase in series units (corrected for in Section 11.3.1), and (*b*) differences in deionizing speeds over, say, the first 100 microseconds following a zero pause for the different breaks, and any other unknown differences.

Mr. Trencham: It is doubtful if the characteristic curve ever becomes asymptotic in practice or in test, since other physical factors enter at these stages. Where an adequate rate-of-rise characteristic can be provided for a given MVA breaker, and in consequence resistance switching is not necessary, the adequate proving of the breaker characteristic must be accomplished whether the R.R.R.V. is used in the rating or not. Also, where resistance switching is adopted the proving that the resistance value is correctly selected for the nozzle conditions and rating over an appreciable rate-of-rise range is essential, for a resistance can be selected that just eases the test circuit sufficiently to get the design to pass the test condition without necessarily ensuring that the resistance has made the breaker suitable for universal application.

Mr. Black: Transient peaks having less than 80% amplitude are ignored by certain American engineers on grounds of simplicity. Our experience indicates no apparent influence on air-blast breaker performance for values below 50%. A better interpretation for double-frequency cases is given in our reply to Mr. McNeill and puts the low-amplitude high-frequency oscillations in better perspective without ignoring them. This preserves continuity and is more nearly related to the generally accepted assessment of the single-frequency transient. The final clearance by the two breaks of a three-phase fault is normally equally shared by the breaks; consequently the severity per break is much reduced.

Mr. O'Doherty: The curves of Fig. 10 typify the inherent normal maximum values for transformers without any parallel loading.

Mr. Cassie: We agree that the rate-of-rise theory does not cover all circuit conditions with the same simplicity as it does a single-frequency circuit, but we feel that to adopt the energy-balance theory would be to introduce a further complication in the circuit-breaker constant K. The range of values that this "constant" may have is not known, but is probably between 10^4 and 10^5 for the different types of breaker in existence. Such differences cannot be conducive to an accurate assessment of circuit severity; the severity of the multi-frequency case can be reliably assessed on the basis of either frequency or rate of rise. Fig. D gives an interesting example, but is unfortunately not supported by any test results and leaves the matter unproved.

Mr. Bruce: The probability of a three-phase test being easier than a single-phase test applies also to certain oil circuit-breakers fitted with arc-control devices when operating at maximum efficiency. Since in nearly every case these breakers are developed as single-phase units and an adequate number of tests is usually carried out to ensure that the worst possible condition with respect to "arc-energy liberation" has been obtained, the severity in this respect is normally in excess of the probable three-phase test severity; this applies also to normal service conditions. Furthermore, the easements in recovery voltage recognized in B.S.116, Part 2, and the very satisfactory performance in service of breakers so proved, demonstrate the adequacy of a three-phase test for air-blast circuit-breakers at or equivalent to 100% recovery voltage.

Mr. Gosland: The apparent anomaly referred to in the rate-of-rise theory with regard to multi-frequency transients can be overcome by the method proposed to Mr. McNeill. The energy-balance theory, while an admirable attempt to find a solution from quite a different approach, is probably more ambiguous than the rate-of-rise theory in its application of assessing circuit severity with the various types of air-blast circuit-breakers.

Dr. Thompson: The experience with the Marx rectifier would appear to be generally analogous to that with air-blast breakers, and, if the characteristic of an instantaneous gain of 30% of dielectric strength can be proved for air-blast breakers, it would be further justifiable to ignore the very high-frequency transients with relatively small amplitudes in assessing circuit severity.

Mr. Garrard: The performance ratio is determined experimentally from correctly proportioned models for identical breaking units when arranged as series elements with the appropriate voltage-control feature. The limiting conditions of performance at voltages proportional to the number of breaks is given by: $P_1 = I_1U_1$, $P_2 = I_2U_2$, $P_3 = I_3U_3$, and $P_4 = I_4U_4$, and the ratios P_2X_2/P_1100, P_3X_3/P_1100 and P_4X_4/P_1100 will be found to fall off with each additional stage as the difficulty of balancing the breaks electrically and aerodynamically increases. Consequently, an accurate knowledge of this ratio is essential if such designs are to be correctly assessed for performance from tests on single breaks. From these experimental data the performance of multi-break circuit-breakers is determined in accordance with Section 11.3.2.

Mr. Cliff: We see no reason why model testing carried out in a scientific manner by research staffs on suitable model designs cannot be used, as in our experience the results have been fully supported by tests on full-scale designs. The models are only scaled down to the extent necessary to enable them to be proved on an existing testing station; hence the degree of extrapolation is restricted.

Messrs. H. E. Cox and T. W. Wilcox (*in reply*): Several contributors to the discussion question our conclusion that resistance switching is the most economical solution to the problem of high-breaking-capacity breakers for voltages above 33 kV.

Some support this scepticism by quoting their own experience in the testing of designs which do not include resistance switching. The suggestion is also made that the case for resistance switching is bolstered up by testing for current-chopping voltages on an artificial circuit using air-core reactors, and thus exaggerating the effect as experienced in service.

We made it clear in the paper that whether resistance switching is or is not justified depends entirely on the natural frequency of the restriking transient (sometimes expressed as R.R.R.V.) for which the breaker is designed. In view of the difficulty of assessing the maximum frequency which will occur in practice, we prefer a type of breaker which is independent of the inherent natural frequency of the circuit. Should the R.R.R.V.'s be limited to figures as suggested in Fig. 10(*a*) of the paper by Messrs. Harle and Wild, our experience would suggest that resistance switching would be unnecessary. Are such low values justified, however, when building for the future? The time has already arrived when the short-circuit current of 132-kV circuits has to be limited by reactors, and this trend will be accelerated as 264-kV or higher-voltage trunk lines become superimposed on the existing 132-kV systems. A much better appreciation of the position would be gained if the results mentioned for the breakers without resistance switching had been accompanied by the R.R.R.V. data.

There is a statistical or chance quality about the occurrence of flashover caused by current chopping, because many chance happenings have to occur simultaneously for the worst voltages to be experienced. Thus, a suitable combination of circuits has to coincide with maximum air pressure on the breaker, maximum electrical strength of the gap (itself obeying statistical laws), and final rupture waiting until the contacts are fully open. This explains the rare occurrence of troubles as reported by Mr. Marshall and Mr. Garrard. It is for this reason that we suggest first of all making the test conditions more onerous than those usually met in practice, and that the test shall be carried out at the maximum pressure and twenty times in succession. Surely the rarity of the happening in service makes a thorough understanding of the problem more essential. Continuity of service demands the complete elimination of all such statistical happenings, and not the adoption of the comfortable philosophy which neglects consideration of the rare occurrence until it actually happens.

It is further suggested that the resistance is unjustified as resistance switching apparently effects no saving in air consumption at 2 500-MVA and 132-kV. Surely it is sufficient justification that the addition of resistance switching enables a breaker to be made that is independent of natural frequency and yet requires no more air than one which has a distinct (and unspecified) limit.

Mr. Amer and Mr. Grant raise the question of the two forms of resistance switching shown in Fig. 8 (a) and (b) and request further information as to why (b) is claimed as more suitable for 33-kV and below, and (a) for above 66-kV. Gap No. 2 of scheme (b) is situated in the downstream side of gap No. 1 and consequently is at approximately atmospheric pressure. It thus requires a much larger gap spacing than gap No. 1. At 66 kV and above, the spacing becomes so large, and hence the air velocity so low, that not only is the design too bulky, but also the arc may fail to clear.

Mr. Amer and Mr. Christie raise questions on the design and testing of the resistors. The resistance value used is so low that even the lowest natural frequency found in service is more than critically damped, and there is thus no need to test at these low frequencies. The resistor does not always cut-in in situations where the breaker can deal with the circuit without its help. If the resistance is required it must cut-in, but if it is not required it may or may not cut-in.

Table A

SCHEDULE OF BREAK TESTS

Test number	Test quantities			Performance times				Equivalent 3-phase rating	
	Breaking current		Phase recovery voltage kV	Arc duration in sec × 10^{-2}		Total break time in c/s		Line recovery voltage kV	Symm. MVA at 132 kV
	Symm. kA	Asym. kA		Shunted arc	Resistor arc	Shunted arc	Resistor arc		
TESTS ON TOP BREAK WITH BOTTOM BREAK SHORT-CIRCUITED									
124	6·72	6·72	61·4	1·1	0·56	2·9	3·2	142	1 530
125	6·78	6·85	60·5	0·68	0·54	2·7	3·0	140	1 550
126	6·72	6·72	60·5	1·6	—	3·3	—	140	1 530
127	9·30	9·30	48·0	0·73	0·58	2·9	3·2	111	2 130
128	9·86	9·86	48·0	1·0	0·44	3·0	3·2	111	2 260
130	10·1	10·2	48·0	1·1	0·56	3·0	3·3	111	2 310
134	11·7	11·7	46·4	1·9	0·45	3·4	3·6	107	2 670
135	11·7	11·7	46·4	1·1	0·61	3·0	3·3	107	2 670
136	11·9	12·0	47·1	1·1	0·51	3·0	3·2	109	2 720
TESTS ON BOTTOM BREAK WITH TOP BREAK SHORT-CIRCUITED									
121	7·17	7·17	61·4	1·1	0·56	2·9	3·2	142	1 640
122	6·78	6·85	61·4	1·2	0·63	3·1	3·4	142	1 550
123	7·05	7·05	61·4	1·1	0·49	2·8	3·1	142	1 610
131	9·86	9·86	48·0	1·1	0·58	2·9	3·2	111	2 260
132	9·70	9·70	47·1	0·96	0·52	2·8	3·1	109	2 220
133	9·70	9·70	48·0	1·0	0·58	2·9	3·2	111	2 220
137	11·9	12·0	47·1	0·22	1·6	2·6	3·4	109	2 720
138	12·1	12·1	46·4	1·5	0·58	3·2	3·5	107	2 760
139	11·9	11·9	46·4	0·29	1·6	2·7	3·5	107	2 720

The resistor can easily be checked in service by means of a Wheatstone bridge, whenever the breaker is overhauled. Each resistor is designed to carry out three make-and-break operations in quick succession based on 1·5 times leg voltage applied. Within 15 min the resistor would be in a condition to repeat such a duty cycle.

We do not believe that resistance switching is required on breakers for 220-kV and higher, unless the rating exceeds 3 500 MVA.

Mr. McNeill and Mr. Flurscheim mention resistance switching using non-linear resistors. Such resistors, while they control current-chopping voltages and may reduce the first peak of the recovery transient, have a very small effect in reducing the R.R.R.V. over the critical range and thus in rendering the breaker independent of the natural frequency of the circuit. They can also be very valuable in controlling voltage division across the series breaks of multi-break breakers. We envisage a line of breakers where the lower breaking capacities are catered for by units without resistance switching, the middle breaking capacities by units with non-linear switching resistors, and the higher breaking capacities by units with linear switching resistors as described in the paper.

Mr. McNeill and Mr. Amer disagree with the contention that the gap is completely de-ionized by the time the first transient voltage peak is reached. It must be remembered that our tests have been confined to mushroom nozzles of the type described in the paper, in which both arc roots are swept into the downstream side of the nozzles and in which only a very small amount of air on the upstream side is "seen" by the arc (due to the shielding effect of the electrodes). For such an arrangement a very close agreement has been found between the maximum value of the first peak of the restriking transient after final clearing and the electric strength as found by our method.

In connection with the impulse tests for finding the electric strength of the gap, Dr. Thompson asks whether oscillating voltages have been considered instead of impulse voltages. Such voltages were considered and were discarded only because the apparatus for generating them was not to hand, whereas an impulse generator and a staff skilled in its use were available. It is probable that more consistent breakdown values would have been obtained with the oscillating voltages. Mr. Forrest suggests that the inconsistencies shown were due to some faulty testing technique and that further investigation would have removed them. It must be remembered that the arrangement used is ideal for demonstrating the essentially statistical or chance nature of breakdown, because the voltage is applied only for a short time and the gap is completely shielded from photo-electric irradiation. Mr. Forrest's suggestion of irradiating the gap by radium would probably have resulted in much more consistent results.

The suggested modifications to the breaking-capacity testing clauses of B.S. 116 are questioned on two grounds. Mr. Flurscheim claims that the background of development testing is the real guarantee and that a specification cannot hope to cover all the possibilities, whilst Mr. Garrard believes that our suggestions are based on experience with only one design. In fact, these are based on theoretical reasoning supported by actual testing of many types of air-blast breaker. Although we agree with Mr. Flurscheim that a very comprehensive background of testing is indispensable, we still believe that every endeavour should be made to devise a specification which proves as many of the possible causes of failure as is reasonable.

Mr. Forrest deplores the large number of insulators between live parts and earth, and stresses the necessity for adequate creepage distance. We fully agree that this is necessary. Up to the present we have had no experience of the use of leaky glazes, but consider this a most promising development.

We are in complete agreement with Mr. Bruce, who makes a plea for single-phase as against three-phase testing, and also with Dr. Whitney's argument for ensuring that tests in which final breaking occurs with less than one half-cycle of arcing be discounted.

Mr. Cliff points out that, whilst the paper describes a method of unit testing, such testing was not included in Table 1. This has since been remedied and the test results given in Table A have been obtained. The fact that the tests were not taken up to the full current and voltage required by the rating of 2 500 MVA and 132 kV is due entirely to test-plant limitations.

DISCUSSION ON

"THE FUTURE OF THE DOMESTIC WIRING INSTALLATION"*

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 6TH MARCH, 1944

Mr. E. L. Morland: Where the cost of a complete electrical installation of a house before the war probably amounted to approximately 2% to 3% of the value of the house, I hope that in the post-war period the figure will not fall below at least 10%. As most of the houses under review are comparatively small, it would be interesting to know whether Government planning and housing authorities are prepared to equip houses in the all-electric sense and provide alternative heating arrangements.

I am surprised the authors do not devote more space to the electric cooker, for which there was an ever-growing demand before the war. On the question of the choice of cooker, I agree that it is not possible to dictate to a tenant, but on one municipal estate of 1 568 houses, 1 501 of the tenants freely chose electric cookers on hire or hire purchase, 58 chose gas cookers, leaving 9 using neither. Also 1 401 chose electric washboilers, in preference to the gas boiler provided free as a house fixture. These figures show the insistence of the housewife to cook and wash with the aid of electricity.

I have found that a 2-kW water heater in the average copper cylinder provides sufficient hot water in most ordinary houses. Why do the authors suggest a 3-kW unit which adds 50% to the load?

Space heating can take many forms, such as inset fires and dispersed heaters, but in whichever form it may be installed, I think the aim should be for the heater to be fixed and not removable so that its use is encouraged on all cold and chilly days, thus tending to improve the load factor.

In the matter of universal sockets, the authors see no need for 15-amp plugs; but a plug which under perfect conditions does its job, when utilized to connect a radiator used for long hours may often develop trouble by heating, whether the plug be flat or round pin. I have long felt that careful consideration still requires to be directed to this problem.

Will the authors explain how, with single-pole fusing, the neutral wire is protected against excess energy in the event of an outside fault connecting it to a live pole?

Regarding the system of wiring, where the skirting board method of installation is adopted the question of metallic con-

* Paper by FORBES JACKSON, W. J. H. WOOD, G. SMITH and E. JACOBI see 1943, 90, Part II, p. 453).

duit does not arise as compound-insulated cables can be used, but in flats with concrete floors it may be necessary to use some form of conduit. I would like to know the type of insulation the authors would recommend for the drawn-in cables.

I agree that the minimum sizes of service cable should not be less than 0·025 in, but I am concerned with services which are of 0·035 in section, many being fully loaded and others likely to be so in the future. I do not at present agree with the provision of a three-phase supply for ordinary domestic consumers.

I think prepayment meters should be discouraged in view of their first cost and the amount of maintenance involved. A scale of charge can be instituted for publicly- and possibly privately-owned houses whereby the tenant pays a fixed sum per week, collected with the rent, a debit or credit being given at the end of the quarter. This scale enables the consumer to obtain practically all the advantages of a prepayment meter. I think standardization of meter-case sizes is also urgently required.

It has been proposed to provide access to the meter from inside and outside the house, but where undertakings still find it necessary to fix prepayment meters I am afraid endless disputes would result, unless the collector took the coins from the meter in the presence of the consumer. The problem of rebate also arises. This suggestion has obvious advantages where meter dials alone have to be read.

One self-contained service unit has been designed to contain the apparatus described by the authors, and which including the meter and coin box occupies a wall space of approximately 20 in by 13 in. This is considerably less than the area indicated in the diagram.

It may not always be desirable for an undertaking to bear the cost of rising mains in large blocks of buildings. The highway authority does not bear the cost of the staircases, or in many cases the cost of staircase lighting. But I agree that the supply undertaking should install these rising mains subject to a suitable financial arrangement with the owners of the property.

Part 2 of the paper is entitled "The Distant View," but a year has gone by since the paper was written and many ideas which were then new are now taking shape. For instance, in the use of fuses, I think a case can be made for the protection of ring mains by fuses or circuit-breakers, each appliance being teed off and suitably protected, according to its load, by a fuse or circuit-breaker so that if the main fuse or circuit-breaker operates it is a simple matter for the layman to clear the ring and try in a new fuse or his main circuit-breaker and then the appliances one at a time. This will quickly show where the trouble lies.

At the end of the paper the training of another type of technician is suggested, apparently to provide liaison between the architect and the electrical engineer. But surely there are and will always be electrical engineers specializing in domestic installations who will be able to convince the architect that he must design a house to take all the various components which together go to form a modern and efficient installation. To bring this about, we must show the public how a house should be built in order to make proper provision for the housing of the electric installations which we should be ready to provide.

Mr. E. J. Mulholland: With regard to the use of specially constructed skirting boards for carrying the proposed ring main for power plugs, could not this idea be adapted for old houses as well? With the co-operation of the builder the existing skirting boards could be removed, and then refixed with screws after the cables had been inserted.

The provision of a conduit to the kitchen from the service position should be a recognized feature in every house, but I suggest that the cables also should be inserted and that this circuit be isolated and controlled by a circuit-breaker with an earth-leakage trip. The kitchen in every house is likely to be the one room in which most of the domestic electrical apparatus will be used, making it essential therefore that some foolproof method of clearing faults should be adopted.

In the authors' sketch of a combined service unit, the incoming cables pass first to the switch terminals. In my experience, this is bad practice, as some means of isolating the complete unit is essential. I think a load of three watts per square foot of floor space is rather high for the average house; at this rating each room would have at least one 300-watt lamp.

Very little mention is made of fluorescent lighting in the paper. In view of the advances made in America, we can surely expect British manufacturers to produce some very attractive designs in the post-war years.

Most persons in the electrical industry when thinking of the future, hold the view that the house or building should be built for the services it is planned to contain. I suggest that consideration be given to the possibility of constructing a house with all rooms connected to a central rising duct, which could contain all the services and which could also serve as a ventilator. This idea might be expanded to give air-conditioning and space-heating as well.

One of the most urgent matters is that current regulations be brought into line with the requirements outlined in this paper. Until this is done no appreciable advance can be made. The use of light-gauge conduit and grip fittings laid in concrete is not considered good practice in the North. In my opinion, nothing but a first-class screwed-conduit job will stand up to the severe conditions met in the erection of reinforced-concrete structures. Even on surface work, light-gauge conduit if subject to a damp atmosphere does not compare with a screwed-conduit job, because of the extra thickness of metal. Lastly, in the matter of continuity, light gauge can give as good a contact as screwed, but it requires extra care, for if a cut is made a little short, the inclination is to steal a bit from each end and thereby lose a certain amount of surface contact. The success of a job depends entirely on good workmanship and supervision.

Mr. T. S. Parkinson: I very much regret that the Architects' Association is not represented at this meeting, because I feel that this paper would certainly give architects much food for thought.

I doubt the authors' statement that few, if any, houses are wired for lighting only. Quite recently, some have been built in the country without being wired at all; gas only was installed, even though an electricity supply was close at hand. Just before the war, prospective builders were putting up houses without even one power plug being installed. Also, if builders wished to cut the cost of a house, the first thing pared was the electrical installation.

I agree with the authors that two or three plugs should be installed in all rooms, and if no more, the conduits for cookers and water-heater. But I do not agree with installing 10-amp plugs only. I still like the 5-amp plug for small apparatus, and the well-tried 15-amp plug for all other purposes, an arrangement which avoids trouble from undue heating.

Have the authors compared the cost of a house wired by the new and the old methods, because the figure of £2 difference in the paper seems very small? Also, it must have been a very small house or flat to be wired for £10. In my opinion, the pre-war builder allowed approximately 2% for the electrical installation of the house, this figure being totally inadequate for installing proper and sound equipment. In fact, I consider legislation should be enacted compelling builders to install proper equipment in the first instance.

I am pleased that the authors take up the question of switching, as in my opinion no one should have to retrace his steps to

switch the light "on" or "off." The switch should always be one step in advance.

The authors have done well in the design of the kitchen equipment, which should be of undoubted value to architects.

Prefabricated skirting boards are an excellent solution, in my opinion, for wiring houses. It would be excellent if all mains of a house were placed in or as part of a moulded-Bakelite skirting board. This question also should be tackled at once, as otherwise skirting boards may be taken up by either the gas or water departments.

The new service equipment is almost past the stage of discussion and is now more or less in the manufacturers' hands. I think that after the war we will have a standard design for service equipment for all houses.

Mr. D. Williams: Before the war, the installation of houses was more or less settled by economic factors, namely the cost of installation against selling points. I think that after the war economic conditions will be very much more stringent, and with the number of houses that will have to be put up the equipment which will go in will tend to be limited. The question of selling points will not arise, so that the idea of putting a large number of plugs in a house will have to be much modified.

Another point is the question of putting three plugs round the skirting board of a room. This is rather a temptation to young children.

Mr. R. Lonsdale: I am sorry the authors have not taken their paper a stage further and given some indication as to how such post-war schemes are to be applied. One of the chief problems in the past in connection with installations on new estates has been to persuade the builders to embody even a minimum electrical installation. In the future I think it will be necessary to impose compulsory specifications for electrical installations; if this is not possible, the public should be educated to demand the proper electrical facilities.

I feel that the authors' suggestions for kitchen equipment suffer from the same objections as others which have recently appeared, namely, they are far too elaborate and costly for the type of house which will be in demand after the war. In designing a kitchen layout I feel that the primary considerations should be: (*a*) a really good cooker preferably of a standard type, the hob to be provided with at least two boiling-plates; (*b*) a means of providing hot water over the sink; a 1½-gallon thermal storage heater would meet these requirements, but with a slight modification of the heater to provide in addition small quantities of boiling water for making tea, etc.; and (*c*) a means of food storage, such as a 3 to 5 ft^3 refrigerator. I think these may be considered the primary requirements, as they are in use many times daily, whereas washing machines, drying cabinets, etc., are only used occasionally and could well be installed later according to the consumers' own requirements.

No doubt the system of wiring adopted will be governed to some extent by the type of building construction employed. I feel that in the past a fetish has been made of conduit systems. Conduit has been installed in situations entirely unsuitable for this class of wiring. A very serious disadvantage of the conduit system when used in small property is the danger from fires due to fault currents being transmitted from conduit to gas pipes. I think that the ideal system for the smaller house is the t.r.s. or plastic cable systems. I suggest that proper channels be provided to accommodate the cables. A continuous insulated earth-continuity conductor should also be run from the various socket-outlet points, switches, etc., this conductor being connected to a terminal block near the service position. The block in turn should be bonded to the lead sheath of the supply cable.

I like very much the service-box arrangement which the authors suggest. Its use, of course, presupposes the adoption of an all-in tariff, which I feel is our best hope for future development.

Mr. W. A. Hatch: What percentage of flats do the authors visualize in the housing schemes referred to? As many of the schemes will be very comprehensive, has district heating been considered?

In Part 1, Section 9, reference is made to *one* circuit for cooker and water-heater. It is conceivable that both these appliances might be in use simultaneously, with a load of 10 kW. Has any provision been included for a drying cabinet, which is an essential accessory in the humid conditions of the North?

Unless very close supervision is exercised, grip-jointed conduit will eventually be a source of continuity trouble, a point emphasized in Part 2, Section 2.1. In the system advocated, how would a break in the continuity be rectified? On the grounds of safety, it seems expedient to include a separate earth wire, especially for the kitchen where there will be so much earthed metal and so many portable appliances.

From past experience with conduit partly or wholly embedded in concrete, it would be well to specify that there must be no breeze, or similar contamination, used in its composition, in order to avoid corrosion troubles.

With the number of plugs advocated, and bearing in mind the size of the rooms, which will undoubtedly have some built-in furniture, it should not be necessary to consider serious alterations, as the positions will be fixed automatically. For lighting, one central, general light should be fixed in each room, and portable fittings used to supplement the lighting of, say, dressing tables, etc.

In Part 2, Section 3, the assumption of 1·5 watts/ft^3 for space heating makes 2 kW for the living room of the house with a floor area of 800 ft^2, as mentioned by the authors, seem inadequate; first because the volume will probably be over 2 000 ft^3, and secondly because of the undue time-lag in warming up.

Mention is made of *driving* equipment for the refrigerator. It is to be hoped that the silent non-drive type will be borne in mind and that the makers of this type may yet be brought back into the electrical fold.

Mr. T. Makin: In Part 1, Section 7, water-heating control during the summer and winter months is mentioned. I am surprised that previous speakers connected with supply authorities have not challenged the suggestion of "on" and "off" sealing. I think that to seal off the water-heating circuit completely during the winter period is an undue restriction on the consumer, and is detrimental to the future of domestic electrical development. Would not superimposed controlled relays be better for this purpose? There are many valleys in the load curves of undertakings even in winter, which can be profitably filled up by water-heating, and the use of suitable controls would enable the heater load to be controlled according to the actual demand on the system.

In the kitchen equipment, the cooking oven could be improved by lifting the bottom shelf 9 in, and placing the griller-boiler unit on the right-hand side above the drawer or cupboard space. This would be very acceptable to housewives, as it would obviate much stooping.

Part 2 does not pay enough attention to the possibility of fluorescent lighting in the houses of the future. It seems a pity that no suggestion for the housing of the necessary chokes has been made in the paper.

[The authors do not desire to publish a specific reply to the above discussion, the points raised having been covered, in the main, in their replies to the discussion before the Installations Section (1943, **90**, Part II, p. 466) and before several Centres and Sub-Centres (1944, **91**, Part II, p. 418).]

A NEW TYPE OF ELECTRON-OPTICAL VOLTMETER*

By L. JACOB, M.Sc., Ph.D., Associate Member.

(*This paper was first received 3rd August*, 1943, *and in revised form 18th February*, 1944. *It was read before the* MEASUREMENTS SECTION *21st April*, 1944.)

SUMMARY

An electronic instrument is described for measuring peak voltages in the range of 2–20 kV, direct or alternating current, to an accuracy of 3%. It has a low capacitance (9 cm) and can be used in some circuits up to frequencies of 1 Mc/s or over. Its action is based on the proportionality theorem for a triode electron-optical system, in that the angle of the beam is defined by the ratio of two voltages: the anode voltage and the voltage of the modulator grid. The beam angle remains constant when both terms of this ratio are multiplied by the same factor, the modulator bias voltage being directly proportional to the voltage to be measured when the latter is applied to the anode. A high voltage is thus measured in terms of a low voltage, the instrument constituting an electron-optical potentiometer. The range of measurement can be extended as desired. The same principle can also be applied to the construction of high-voltage tubes so that they act as their own voltage-measuring instruments.

(1) INTRODUCTION

Developments in electron optics have led to an investigation of the properties and characteristics of electron beams and of electron-optical systems generally. It was early realized that one of the fundamental laws of this branch of optics, namely that the trajectory of the electrons in any lens field depends only on the voltage ratio of that field,† could be employed with a reasonable degree of accuracy for the measurement of voltage, once the system had been calibrated. It was also demonstrated‡ that with the cathode-ray oscillograph an unknown voltage could be measured by observing the deflection produced on a beam of known velocity. Both these applications have been embodied in instruments, mainly for laboratory use, although the accuracy obtained is not high unless very special precautions are taken.

A property of the "immersion lens" can also be applied to the same end. In this lens system, the beam angle at zero modulator bias is independent of the accelerating voltage, neglecting any initial velocity effects. Also, the beam angle at all accelerating voltages varies linearly with the modulator bias from zero at the suppression point, to the full beam angle when the modulator is at cathode (or zero) potential.

The new voltmeter is based on an application of these two properties, and, theoretically at least, there appears to be no limit to the voltage which can be measured with it. The present range is, however, limited to between 2 and 20 kV, direct or alternating current.

(2) THEORY OF THE INSTRUMENT

An "immersion" objective is shown in Fig. 1 and consists of an object (oxide cathode) C, a modulating electrode M and an accelerator A. It derives its name, by analogy, from the "immersion" objective of physical optics, in that the cathode is immersed in and forms part of the lens field. The electrons enter the field with very small velocities; there they are accelerated and emerge as a beam through the aperture in the modulator M, ultimately reaching the anode, which if coated with fluorescent powder defines the beam diameter d at the screen.

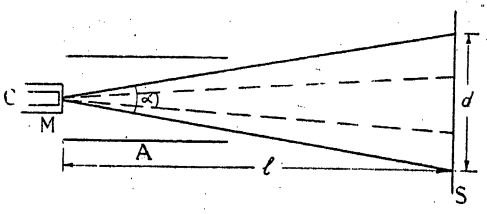


Fig. 1

The angle of the beam is determined by d/l, and since l, the distance from the crossover to the screen, is for all practical purposes fixed, the diameter d alone determines the angle of the beam. d is found to vary linearly with variations in the potential difference between M and the cathode. The modulator M acts in some ways as an iris diaphragm, as it varies both the electron flux which passes through to the screen, and the beam angle. It does not generally act as a "stop," since the beam diameter may be much narrower than the diameter of the aperture through which the beam passes.

The action of the modulator is best understood from the field distributions shown in Fig. 2. In (*a*), M is at cathode potential,

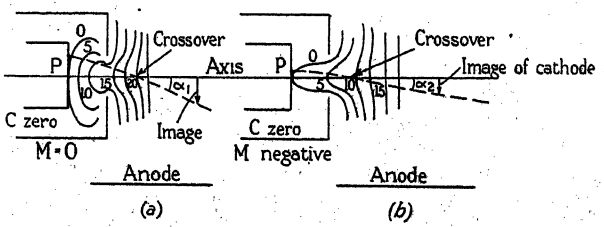


Fig. 2.—Field distribution of C/M/A system (diagrammatic).

and the zero equipotential which lies along the cathode surface then embraces the maximum area of cathode emission. The electrons leaving the surface of the cathode at all angles are focused by the field to form an image of the cathode in the region of the modulating electrode. This image is generally smaller than the original emitting area. Between the cathode and its image, the rays form the crossover which is normally much smaller than the cathode image. In the present instance, the rays radiating from the crossover are not further focused, but travel rectilinearly to strike the graduated screen at the end of the tube.

In tubes used for television purposes, these rays are again focused by a double-cylinder lens to form the small scanning spot on the screen. As this is usually an image of the crossover it is the smallest spot that the tube will give. Whether the rays have passed through the crossover or are focused into the final spot, the maximum current density in the beam cannot exceed a theoretical limit which, according to Langmuir,† is given by:

$$\rho_{max} = \rho_{cath}(1 + Ve/kT)\sin^2\theta$$

where V is the final accelerating voltage, ρ the current density, e the electronic charge, k Boltzmann's constant, T the absolute temperature of the cathode, and θ the semi-angle of the beam.

* Measurements Section paper. Communication from the staff of the Research Laboratories of The General Electric Company, Limited, England.

† FÜNER, E.: *Zeitschrift für technische Physik*, 1934, 15, p. 582.

‡ MEISSNER, M.: *Archiv für Elektrotechnik*, 1933, 27, p. 335.
EHRENBERG, W., and JAESCHE, H.: *Journal of Scientific Instruments*, 1943, 20, p. 161.

† LANGMUIR, D. B.: *Proceedings of the Institute of Radio Engineers*, 1937, 25, p. 977.

This equation defines the limitations on current density at the crossover. At the cathode a limit is imposed by its life.

When the modulator is at the potential of the cathode, the voltage ratio thus being infinite, the electron trajectory shown in Fig. 2(*a*) passes through the crossover and defines the maximum beam angle. If the geometry and the configuration remain unaltered, the cardinal points of this lens system will remain fixed, irrespective of the voltage at the anode.

If the potential on M is made negative with respect to the cathode, as in Fig. 2(*b*), the field distribution will alter with each new setting of M, because every variation of the voltage on M affects the shape of the field on each side of M. Whereas when M is at cathode potential the zero equipotential line embraces the maximum area of cathode emission, when M becomes negative with respect to the cathode this area contracts in proportion as the negative bias is increased towards the cut-off value. At this point, the emitting area, and with it the beam angle, is practically zero. The voltage applied to M thus affords a means of controlling the angle of the beam.

The condition of zero current, i.e. at cut-off, is given by the ratio of anode volts E_A to modulator volts E_M, i.e. $\mu = -E_A/E_M$. The cut-off point is then defined exclusively by this ratio, provided the geometrical relationships remain unaltered. This gives one of the methods of using the instrument.

The beam angle can, however, be kept constant at any desired value by adjusting M for each value of the accelerating voltage, since in any three-electrode gun the simple proportionality theorem of the triode holds.

An analysis of the equation for the electron trajectory in the electron-optical system, e.g.

$$\ddot{r} + \dot{r}\dot{V}/2V + r\ddot{V}/4V = 0$$

shows that it is homogeneous, and that the height of the ray r at any point in the field depends on the potential V and its derivatives at the corresponding point on the z axis. Hence, if all electrode potentials be multiplied by the same factor, the path of the ray will be unaffected, although the space-charge current will, as usual, increase in accordance with the $\frac{3}{2}$-power law; in other words, the beam angle will remain constant. This gives the second method for using the instrument.

Fig. 3 shows the theoretical linear relationship between beam

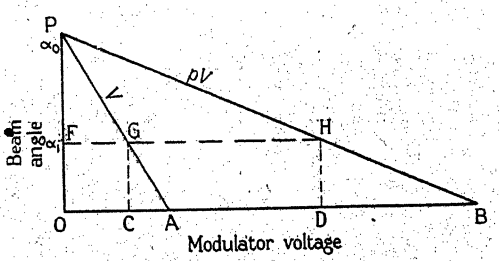


Fig. 3.—Beam angle and modulation.

angle and modulation voltage for two different accelerating voltages V and pV. Following the fundamental principle, the two curves intersect at a point P representing the beam angle α_0 when $M = 0$. This angle is constant and independent of the accelerating voltage under these conditions. The points A and B define the cut-off points for the beam at each voltage. Since $OB = p\,OA$, then if OA and V are known, any voltage can be measured. At or near the cut-off point, there is negligible current flow to disturb the voltage source, and the measuring conditions are ideal. Very good and consistent visual observations of the cut-off point can be made by the same observer. More refined methods using a Faraday cage placed behind the screen can be used to determine the modulation point at which the beam just begins to appear.

The second method of using the instrument, which gives the more accurate results, is to keep the beam angle constant (not zero as at cut-off) at all accelerating voltages, i.e. by adjusting M. In Fig. 3, if $OB = p\,OA$, then $DB = p\,CA$, so that the voltage up from cut-off to give a constant beam angle α enables p to be determined, which in turn gives pV, the unknown voltage. The constant beam angle can be read from a scale engraved on the screen, or determined with the Faraday cage placed behind a slit which catches the "spill-over" of the beam defining the constant angle.

A third method, which does not give such accurate results, keeps the modulation voltage constant and observes the variation of beam angle with accelerating voltage.

(3) THE EXPERIMENTAL VOLTMETER

The model voltmeter is shown in Fig. 4A and a diagram of the instrument in Fig. 4B. The "immersion" objective C/M/A

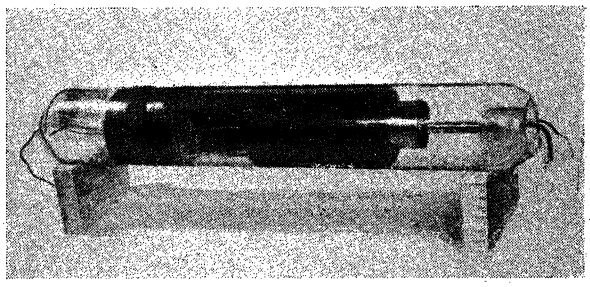


Fig. 4A.—Electron-optical voltmeter.

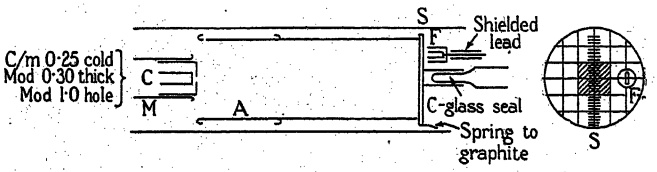
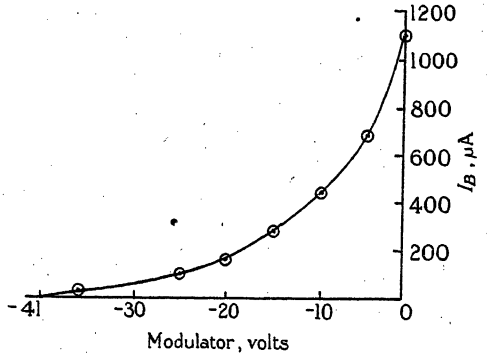


Fig. 4B.—Experimental voltmeter.

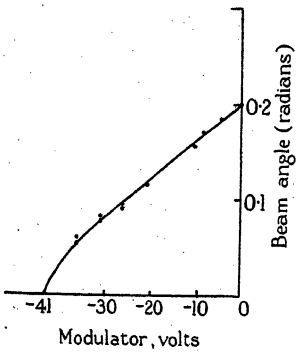
consists of an oxide cathode surrounded by a modulator with 1-mm aperture and an anode cylinder, 37-mm diameter and 60 mm long, mounted coaxially to it. The screen S of $\frac{1}{8}$-in copper is supported by three legs welded to the inside of anode A, and is placed 220 mm from M. It is engraved with squares of 5 mm side and with a millimetre scale along one diameter, for use when working at constant beam angle. A fluorescent powder is embedded in the engraved lines and also spread over the four central squares for use in the cut-off method. A Faraday cage F with a slit 0·25 mm wide is placed 20 mm from the centre for use in the "spill-over" method.

The whole accelerator-screen system is mounted on the copper tube forming the copper-glass seal at one end. A layer of graphite covers the glass wall from the centre of A past S, with a window cut opposite S to enable the base of the beam to be observed. The capacitance of the instrument is 8·8 cm.

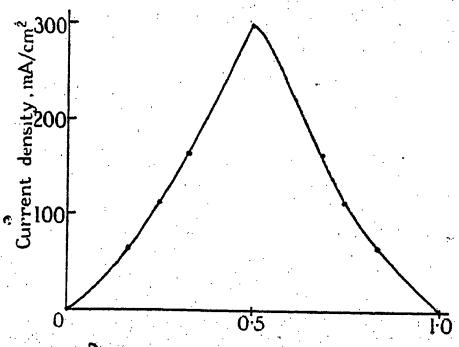
The tube of the experimental voltmeter was baked-out using a 3-stage mercury-vapour pump, and the oxide cathode flashed at 6 volts, i.e. at 50% overload, to decompose the carbonates. The electrodes were degassed by eddy-current heating for 20 min to remove surface gas. The tube was then aged up to 35 kV before bringing down the getter and sealing off from the pump. The modulation characteristic shown in Fig. 5(*a*) was obtained on the sealed-off tube at 5 kV, where I_B at $M = 0$ is about



(a) Modulation characteristic, anode at 5 kV



(b) Beam angle



(c) Current density distribution

Fig. 5

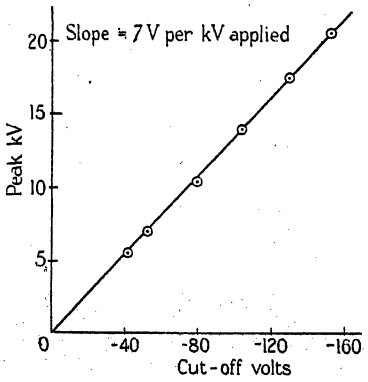
1 milliamp. To obtain the current at any other accelerator voltage, the $\frac{3}{2}$-power law is used; thus at 20 kV, I_B at $M = 0$ is about 8 milliamp. Fortunately, the tube is never used under such conditions, since, as the voltage increases, the negative bias is increased in proportion to maintain the beam diameter constant. The current at the highest voltage thus rarely exceeds 1 milliamp, though by suitable design it could be reduced to 1% of this, if necessary.

(4) BEAM CHARACTERISTICS

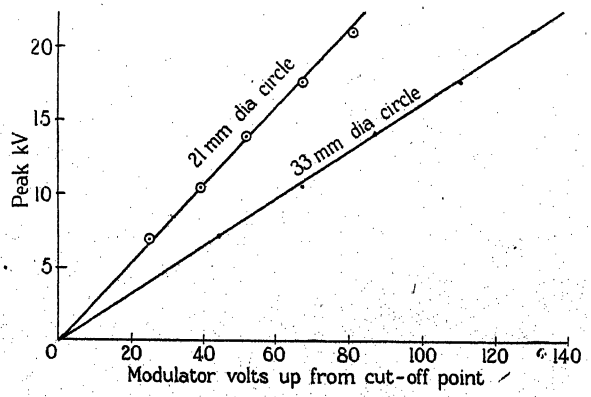
(4.1) Angle, Distribution and Space Charge

Both the angle and distribution of the beam are of special interest; they are shown in Fig. 5(*b*) and (*c*) respectively for an accelerating voltage of 5 kV. It will be noted that in (*b*) the relationship is linear over at least three-quarters of the modulation range. The curve as drawn does not pass through the cut-off point at $M = -41$ volts, because at these small angles the patch of light seems to disappear suddenly when it has been reduced to a few millimetres in diameter. This may be a physiological limitation, but it does not affect the linear proportionality between V_{BO} and V_A.

The current density across the beam was explored in a demountable tube using a Faraday cage with a 0·6-mm hole at the centre. This was moved along a diameter of the beam, and the current density measured in the plane of the cage was used to calculate that at the modulator aperture. This calculation was simple and was shown to be valid (*a*) by the electron-microscope effect and the large depth of focus, proved by substituting an "illuminated" gauge for the cathode, and (*b*) since work on other lines has shown that the emitting area for this system is approximately that given by the area of the aperture in the modulator. Fig. 5(*c*) shows that at 5 kV the peak current density is about 300 mA/cm² and that there are no large tail effects; the ratio of peak to mean is about 3. On modulating back, as when making



(a) Cut-off calibration



(b) Constant diameter calibration

Fig. 6

voltage measurements, the form of the distribution curve is similar, the tail effects being even less marked. This limited development of the tail is helpful when using the "spill-over" method, since the edge of the beam is then more precisely defined.

The effect of beam-spreading due to space charge is negligible, as indicated in the Table. The calculation for each point is given in terms of R, the ratio of expanded to normal beams, i.e. the beam width at the screen, with and without space-charge effects, for the linear and angular dimensions obtaining in the instrument.

Actually, the space-charge effect is maintained constant as long as the conditions of calibration remain unaltered; it does not in any way affect subsequent measurements.

Table

Direct current	Modulation voltage for constant $\alpha = 0{\cdot}095\ r$	I_B for constant $\alpha = 0{\cdot}095\ r$	Average current density at source	$R = \frac{\text{Expanded beam}}{\text{Normal beam}}$
kV	V	μA	mA/cm²	
3·53	− 13	112	14·2	1·0072
5·0	− 19	190	24·1	1·0072
7·05	− 25·5	318	40·4	1·0072
10·6	− 38	585	74·5	1·0072
14·1	− 50·5	900	114	1·0072
17·6	− 63·5	1 160	148	1·0072
21·2	− 76	1 530	195	1·0072

(5) VOLTMETER CALIBRATION

The instrument is calibrated with a 50-c/s alternating current and Abraham electrostatic voltmeter connected to it in parallel. The measuring beam was generated at the 4-volt cathode, and the beam angle altered by varying the 240-volt direct-current (battery) supply across the modulator.

Two methods of measurement were used: (*a*) a cut-off method, in which the suppression point of the beam, as judged by the disappearance of the fluorescent spot on the anode, was observed by reading the negative modulator voltage for each high voltage; and (*b*) the constant beam-width method in which M was adjusted at each voltage until the diameter of the beam was constant or "spilled-over" into the Faraday cage. To avoid the effect of stray fields, the tube during calibration and subsequent measurements was completely enclosed in a Mumetal screen, except for a window. Both methods gave results in good agreement; readings were also satisfactorily reproducible.

Fig. 6 shows that in method (*a*) the slope was about 7 volts modulation per kV applied and the cut-off point was constant to about 1 volt in all cases, i.e. the error is constant at about 3% at quarter full-scale. This places the instrument in the low-error class for high-voltage measurements.

In method (*b*) the linear relationship expected was realized for two diameters of beam; in other words, if the bias is doubled, then the applied voltage must also be doubled to keep the beam width measured at the screen constant. In this method the accuracy depends on the method of detection; visual observation of the width of the beam gives an average accuracy of 5%, while the "spill-over" method applied to the edge of the beam gives an accuracy within the 3% limit.

The instrument measures peak voltages only and gives no information regarding the wave form. It can be used without appreciable error in certain circuits with frequencies up to 1 Mc/s, because even at the lowest anode voltage the transit time is only one hundredth of a cycle, and the instrument is thus free from the time lag which occurs with the standard spark gap. The instrument should prove very helpful in measuring rapidly fluctuating voltages of widely different wave forms, and where voltage values found with a spark gap are definitely known to be unreliable.

DISCUSSION BEFORE THE MEASUREMENTS SECTION, 21ST APRIL, 1944

Mr. L. C. Jesty: What appeals to me about the author's device is that it is yet another application of the cathode-ray beam, as well as the extreme simplicity both of the design of the voltmeter and of the fundamental principles on which it is based.

With regard to the electron-optical principles, has the author any evidence of the effect of space-charge, as described in Section 4.1, when current saturation is approached? It is clearly possible to design the tubes so that within the range in which they are used current saturation does not occur, the beam always being fully space-charge-limited. On the other hand, if the tube is used, deliberately or accidentally, outside this range, I feel that there must be some correction to be applied to the calibration. For example, the diagram shown on the screen revealed the difference between the field in the immersion lens in the space-charge-limited and non-space-charge-limited conditions. That difference will obviously occur in operation, if the device is taken out of the space-charge-limited into the current-saturated condition; it will alter the focal length of the first lens and the focusing of the beam, and thus require some correction of the calibration. It would seem legitimate to use the device in that way, with suitable correction.

Mr. A. Morris Thomas: I have considered the possible field of application of this instrument. First, it has to be calibrated, and therefore depends on the accuracy of the standard; in this respect it is not inferior to any other form of high-voltage peak voltmeter. Secondly, it is much superior in one important respect, in that a low-frequency calibration can be used for any operating frequency up to 1 Mc/s.

Several forms of high-voltage peak voltmeters are suitable for use at low frequencies and capable of fair accuracy. The best types are connected directly to the high-voltage source, the most commonly used being the voltage-rectifier type and the current-rectifier type. The voltage-rectifier type is used with a capacitance voltage divider which requires careful design, while the current-rectifier type is used with a high-voltage capacitor, but does not, in general, function accurately if the waveform of the voltage has more than one peak. Both types give continuous readings, this being an essential requirement for the majority of applications; moreover, their power consumption is usually insignificant. Also, they have the advantage of enabling measurements to be made remote from the h.v. conductors; in this respect the author's instrument seems to be at a disadvantage, and as a continuous-reading instrument it has rather a low accuracy. The author reports an accuracy of 5%, but, according to the data given in the paper, with a circle 20 mm in diameter and the marks spaced at 1 mm the accuracy is about 10%.

It seems that if such an instrument could be produced fairly cheaply it might be used for l.f. work on grounds of compactness; but it is likely that its main application will be in the h.f. region, e.g. radio transmission and h.f. industrial heating. In these cases the l.f. form of high-voltage peak voltmeter becomes inaccurate, owing to stray capacitances and self-inductance.

As far as I can see, however, the electron-optical voltmeter offers little advantage over the sealed-off type of ordinary cathode-ray oscillograph, except that the latter requires a capacitance voltage divider at high voltages, and therefore suffers from the inaccuracies at high frequencies already mentioned. On the other hand, as the author states, it will not delineate the waveform.

A use for this voltmeter might be found in the measurement of slow surges, such as occur on ignition systems. With these a crest voltmeter takes some time to charge up, and is therefore unsatisfactory, while an oscillograph involves photography. Would the author therefore state the range of such slow surges which could probably be measured; also, whether the calibration of his voltmeter is maintained throughout the life of the instrument, or how often recalibration is desirable?

Dr. H. Moss: One point which occurs to me with regard to the use of this meter, of which we have had some experience in research work is the lack of resolution on the circle obtained on the screen. I should have thought that the accuracy of measure-

ment was more of the order of 10% over quite appreciable ranges of the instrument, on account of the lack of definition at the edge of the circle.

In our work we noticed another trouble which still lacks an explanation, namely that the image is frequently slightly elliptical. We found that the difference in the major and minor axes on certain types of instrument was about $\pm$ 7%.

Another feature giving some anxiety is the precise linearity of the law connecting the beam angle and the modulator voltage. We found that departure from this law was about 2 or 3%. Perhaps the author can throw some light on this divergence.

There is a type of electron-optical voltmeter to which I should like to refer, which operates on totally different principles. It has certain interesting features, and depends on electron diffraction. I did some work on this five or six years ago from the point of view of the engineer, not of the physicist, to whom the phenomenon is well known. Briefly, an electron beam has a dual nature. From one angle it may be regarded as a stream of charged particles, while when it reacts with thin films of matter it exhibits essentially a wave nature and the beams are diffracted in much the same way that X-rays are diffracted by much larger masses of matter. This phenomenon can be used to provide a very accurate form of electrometer. In my device the diffracting material was a colloidal film of graphite, through which a high-voltage beam was passed; on the exit side of the graphite there was a fluorescent screen on which the diffracted electrons appeared. The diameter of one particular ring, usually of Miller indices (110), is measured, and from this and the distance between the screen and the graphite diffracting material the wavelength of the associated wave train connected with the beam can be deduced. Then by applying some simple principles of wave mechanics the volt velocity of the electron beam can be determined. This method is truly absolute; and no assumptions other than that the fundamental law holds and that the crystal size of the graphite is known have to be made. It is purely for use with direct current and does not seem at all amenable to alternating current. I should like to hear the author's opinion of this method of measurement.

Mr. P. G. A. H. Voigt: When the author was demonstrating the instrument, he mentioned that it is rather tiring to the eyes. What I observed may not be what occurs under normal working conditions, but, as far as I could see, the target when illuminated was extremely bright, and would dazzle any close observer. This makes it very difficult to observe a very faint spot subsequently. If this is the cause of the trouble, a photographic filter on a little flap placed in front of the target while the latter is brightly illuminated would cut out the dazzle. The filter could then be lifted and observations made until the spot just appeared.

Prof. J. T. MacGregor-Morris: To me it is extraordinarily interesting to see the developments which have taken place in cathode-ray measurement since I originally pioneered it in 1901, when a Wimshurst machine was used as a source of supply.

The present instrument strikes me as being very simple. Several instruments are available for measuring up to 20 000 volts. In the high-voltage laboratory at Queen Mary College, for example, Prof. John has had to measure voltages from 20 kV to 1 000 kV, and I should like to ask the author what proportions his apparatus would assume if it could be applied to these high voltages. How far is this instrument capable of measuring the maximum value of a single transient, where the transient falls to half value in, say, 50 μs?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Dr. L. Jacob (*in reply*): Mr. Jesty has raised an interesting point. While it is true that suitable design can ensure space-charge conditions, nevertheless the introduction of saturation might possibly necessitate a recalibration.

In reply to Mr. Thomas, continuous reading is achieved by observing the edge of the beam at a fixed modulation voltage. As regards accuracy, the cut-off point can easily be obtained to 1 in 30, and the 21-mm circle shows an accuracy of 1 in 20 when reading-off angles. Slow surges should be measureable over the calibration range, which normally does not alter with time.

Provided the same edge of the beam is used throughout, the calibration will not be affected by assymmetry of the beam, and it should include the variations from strict linearity which Dr. Moss points out. The 7% variation mentioned by him may result from mechanical defects, as it is exceptionally high. The diffraction voltmeter which he has used is a tribute to his skill, but its failure on alternating current and the difficulty of interpretation exclude it from most commercial laboratories.

The use of a filter to relieve eye strain, as recommended by Mr. Voigt, can be helpful. Generally, however, it is not required in the cut-off method. As regards future design, a cascade system is indicated for 1 000 kV, which would be some 6 ft long.

In reply to Prof. MacGregor-Morris, single transients could be measured, provided the transit time was considerably less than the time of build-up. Here, a suitable holding-off voltage might be necessary.

THE ELECTRICAL ASPECT OF FARM MECHANIZATION*

By C. A. CAMERON BROWN, B.Sc., Associate Member.†

(*The paper was first received 9th November*, 1943, *and in revised form 9th February*, 1944. *It was read before the* INSTALLATIONS SECTION *13th April*, 1944.)

SUMMARY

This paper has been prepared with the dual purpose of presenting to those interested, but not actively engaged, in rural electrification, a picture of the general development of electrical participation in farm processes, while at the same time offering a clearing-house of ideas for those actively engaged but whose interest is, for various reasons, localized. The main attention has been given to the less-common applications, to those which are the subject of some controversy, and to those which may appear to have a wider field of application in the future. Emphasis has been placed on trends rather than on facts and figures.

(1) INTRODUCTION

The main reason for the outstanding war-time success of British agriculture has been the application of an extensive mechanization, the major part of which has been applied to field processes.

In none of this major farm mechanization has electricity taken any part. It is indeed difficult to visualize, in the light of our present knowledge, a practicable type of electrically-driven field power unit having the versatility required in war-time. It is perhaps to be regretted that there had not been developed a machine suitable at least for co-operative or contract working to undertake the heavier field work on a number of farms. In certain of our more highly electrified rural areas with connections on the 50% mark, such a service could have contributed something quite substantial to the reduction of the consumption of imported liquid fuel.

Nevertheless the war conditions have brought about a greatly increased appreciation of the need for, and value of, good ancillary equipment in and around the farm buildings. Here electricity and electrical power have been in outstanding demand and have given very great service. Most of the old shibboleths of comparative fuel and Diesel-oil costs have disappeared, ease of handling, reliability and labour-saving being the overriding requirements which the farmer finds to be best met by electricity. In the course of fairly wide inquiry over a wide range of both farm conditions and tariffs the author has found no indication whatsoever that the bargain is accompanied by running costs which the farmer considers to be unreasonable—on the contrary he has, more often than not, dismissed them as one of the minor items of farm expenditure, as indeed they are. Even the bogy of the past—contributions towards cost of connection—rarely crops up as an obstacle, farmers now being generally willing, and apparently able, to pay costs which were once not given even a second consideration.

It is not the purpose of this paper to make a case for the increased use of electricity on farms, but rather to present a survey as has been done from time to time in the past, of the current practice in applying electricity to farm operations. It is proposed, too, to treat the applications critically and constructively, and in general to devote rather more space to certain promising lines of applying electrical power which are in but the early stages of development than to operations which are already well known and established.

* Installations Section paper.
† British Electrical and Allied Industries Research Association.

(2) GENERAL TRENDS

(2.1) Extent of Use on Farms

While it is not within the scope of this paper to examine the wider issues of rural electrification or to enter into discussions on the comparative degree of rural electrification in this country and in others, it is legitimate to take the opportunity of dispelling a misunderstanding as to the extent to which electricity is used on farms.

It is surprisingly widely believed, and not entirely in lay circles, that the supply of electricity to farms is mainly a matter of the amenities—lighting and perhaps a radio set—and that little use is made of it in actual farm operations. This view was given somewhat surprising support[1] some time ago by a statement to the effect that ". . . electricity plays a negligible part in agriculture at the present time and is confined to lighting the farmhouses when they are adjacent to local supplies. There are, of course, isolated cases where farmers have utilized electricity to drive all their plant . . ." Such a statement is hardly complimentary either to rural supply engineers or to farmers. Unfortunately, while it is a statement and a belief which any engineer connected with rural electricity supply knows well to be untrue, it is difficult to find statistics separated in a form which will enable it to be disproved.

The author has, however, been fortunate in obtaining relevant figures from eight supply undertakings operating rural areas.

DEGREE OF POWER UTILIZATION ON FARMS.
FIGURES FROM EIGHT RURAL AREAS*

Area	No. of farms connected	No. of farms using motors	No. of farm motors in use	Total h.p. of farm motors	No. of electric sterilizers
A	701	526	808	—	28
B	688	444	585	—	107
C	937	—	657	—	—
D	—	166	182	—	18
E	707	602	—	2 810	25
F	239	204	—	808	10
G	61	33	42	—	6
H	800	270	818	—	60

* Where no entry is made, separate statistics are not available.

These are good areas, probably amongst the leaders in rural development in this country, but no apology is made for quoting them, since critics of our rural electrification invariably generalize on the worst cases here and refer to the best cases abroad. At the same time, the author has no reason to believe that these figures cannot be matched—if not, indeed, excelled—in several other areas, and he does not consider that the average of all the areas in the country in respect of motors installed would be substantially lower. It may therefore be accepted that the majority of farms *do* make use of electricity for power purposes.

(2.2) Trend of Farm Power Developments

The general tendency in the period between the two wars has

been in the direction of a reduced use of mechanical power in and about the farm buildings. This was largely due to a gradual diminution in the preparation of foodstuffs on the farm, the requirements for stock feeding being more easily met by purchasing ready-prepared rations of one kind or another. Such tendencies were symptomatic of a period of discouraged—if not, indeed, lazy—farming.

There remained, nevertheless, a hard core of level-headed farmers who were not altogether lost to the tactical advantages attaching to absolute control over what was fed to their stock, and who also considered that it was more economical to make up the rations on the farm. By the late 1930's this view had spread so that by the outbreak of the war there was a distinct and increasing tendency for farmers to resume home grinding. This did not, however, mean home growing, as most of the grain so ground was bought and many of the economies so effected were due to wise purchasing. The war, however, has altered the whole position and has added home growing to the urgent reasons for home grinding. Thus we see a widespread increase in demands for farm grinding equipment.

The related processes of chaff-cutting and root-slicing have not regained their position in the same way. The feeding of hay, straw and even roots whole made headway during the between-period, and there is no sign of any appreciable tendency to revert to the machining processes.

Threshing has, of course, lost something in prominence by the advent and growth of the combine-harvesting process, which cuts and threshes in one operation on the field. It may not, however, have lost anything in value, as the increase of grain crops due to war-time ploughing is mainly on lands unsuited to combining and therefore contributes to the thresher's load. As an electrical load, however, it has grown but little, if at all, during the war, partly because the compulsory decentralization of stocks favours field threshing and partly because the bulk of the threshers now being manufactured are travelling machines provided for or on behalf of the Ministry of Agriculture.

Combine-harvesting has, however, been accompanied—indeed only rendered possible—by the development of grain driers, which are now considered to be essential if combining is to be successfully carried out, even in the drier parts of the country. Electricity is recognized as being pre-eminently suitable for providing the motive power for all types of grain-drying plant, and an effort is invariably made to secure a supply for this purpose. Grass-drying has hardly lived up to the bright promises of its early days, but it is quite appreciably practised on a somewhat more moderate scale than the highly intensive processes once advocated; here again electrical power is always asked for.

On the dairy farm, and in the dairy section of the mixed farm, a much brighter and more progressive note has been persistent throughout even the leanest period. Milking machines have been installed steadily and in spite of certain controversial episodes, and in war-time this has been accentuated to a degree only limited by lack of materials. Standards of hygiene have improved —largely under pressure from official sources, it must be admitted—and because of its essential cleanliness electricity has been adopted for sterilizing and water-heating unless some overriding factor has ruled it out. This, too, has been accelerated by war-time conditions, not, it must be admitted, so much on solely hygienic grounds—standards appear to be somewhat relaxed in this respect—as on account of labour-saving, and reliability as compared with coal supplies.

During the past 20 years there has been a welcome and increasing appreciation of the value of an adequate water service, and in no application has electrical operation, with its possibilities of automatic control, appealed more.

(2.3) Reactions of the Farmer

Farmers are traditionally conservative, and, if one may judge by the sometimes unfortunate experiences of the comparative few who have been outstanding contradictions of this generalization, they could hardly be blamed for being so. It is, however, only a generalization and an exaggeration, and if farmers appear to be slow to accept new ideas it must be remembered that the standards and developments by which they must judge the practicability of a new idea are themselves long-term and slow-moving. Farmers have not, in general, been slow to adopt improved methods in their fields, once these have become demonstrably sound.

They have, however, been slow to adopt labour-saving methods in and about the farmyard, and the philosophy with which the farmer will put up with cumbersome and slow manual operations always astonishes the engineering observer. Particularly surprising is the amount of sheer lifting which is done manually. In the past farmers have probably not considered that they were called on to make life more pleasant for their employees, but they must have received something in the nature of a shock to find that man-power is most expensive. In a paper before the Royal Society of Arts[2] Bomford claimed that the cost of human power is 10s. per h.p.-hour, and showed that with even 1 h.p. at his disposal a man's output can be increased 8 times. Wright,[3] too, has stated that the future of agricultural mechanization lies in the direction of eliminating hand labour. The farmer's reception of these ideas has been hastened by the war, by the shortage and rising cost of labour, and by the fact that some of the labour available—e.g. the Women's Land Army—cannot tackle the heavy jobs once performed by men. In such of this movement as applies to the multitude of operations round and about the farm buildings, electricity is the obvious medium and is recognized as such by all farmers who are fortunate in having a supply.

There is no royal road to satisfying farmers' requirements, which may—and often do—vary in different parts of the country, or indeed county, for what appear to be identical conditions. A case in illustration is grinding, where the provision of a standard machine is complicated by the demand for different types of output for the same class of feeding.

(3) GENERAL OBSERVATIONS

(3.1) Motors

In spite of attempts from time to time to make a case to the contrary, there does not seem to be any call for a special "farm motor." It is difficult to think of any power application on the farm which cannot be met from the wide range of industrial motors. Only the simplest types are required, the ordinary protected type having shown itself capable of meeting almost all farm conditions, although, of course, there are obvious places, e.g. where water splashing is likely, where totally-enclosed types are necessary. The most universal enemy on the farm, however, is dust, and some engineers are chary of installing other than totally-enclosed motors for this reason. Danger from this cause is, however, overrated. Farm dust is comparatively innocuous compared with the dust found in mining and certain industrial processes, and has little, if any, corrosive or abrasive qualities; the only potential danger is a possible complete blockage of the working parts by sheer weight of dust. Where, therefore, there is any need to economize on the installation there is generally no need to go to the extent of fitting totally-enclosed motors. It is not even essential in slip-ring motors but is absolutely necessary in motors incorporating brush-lifting devices.

While the advantages of the polyphase motor are generally admitted, there is no longer the tendency to regard single-phase

motors as a temporary expedient. Large parts of the country are now almost entirely served by single-phase supply, and such undertakings as the North-Eastern, Wessex, Yorkshire Electric Power, Mid-Cheshire and Dumfriesshire take almost any farm power requirements in their stride with single-phase supply. Manufacturers of farm power units must therefore be prepared to cater for either single- or three-phase supply.

The idea, once prevalent, of using transportable motors to be taken from job to job has never developed far, and indeed it is practically dead. This is quite understandable. In the first place, the small motor, up to 5 h.p. or so, which can be transported comparatively easily, is in fairly constant and daily demand for each job, and the farmer does not want to be faced with the trouble of frequent disconnection and transportation. Also, farmers find that, the cost of motors being low in comparison with that of their previous power units, the saving in capital outlay effected by using portable motors is not worth the inconvenience entailed. The G.E.C. Drumotor was probably the most ingenious and notable attempt to simplify the problem of the multi-purpose motor; had farmyards possessed smooth and clean paving there is little doubt that this motor would have done much to encourage the use of portable motors, but a few experiences of trundling the set through a muddy yard must have been very discouraging. There are not, however, the same objections to mounting very small motors—1 h.p. and below—in such a way that they can be bodily removed and temporarily remounted for short-period seasonal jobs (Fig. 1).

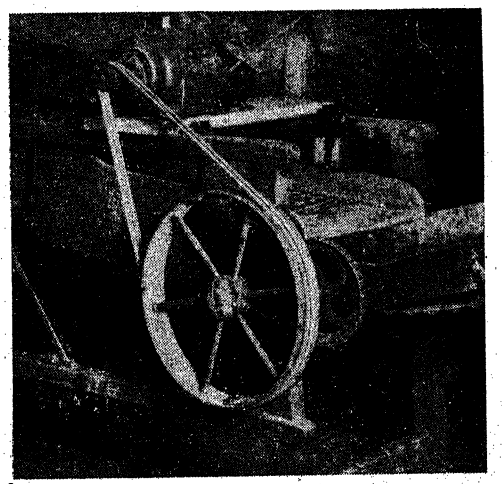


Fig. 1.—Small motor on temporary mounting for driving potato sorter.

There has been a rather stronger tendency to make use of the larger motors for multi-purpose ends and to make them transportable. This enables the same 15- or 20-h.p. motor to be used for, say, silage cutting, threshing and log-sawing, none of which need overlap, and each is an operation which can be carried through to a finish in a matter of a few weeks. On some farms where grinding is carried out only during winter the motor can be locked up on that job for the winter months.

Several makers provide motors of the above sizes on a transportable chassis, and this requires a tractor or horse to move it from place to place. For making an existing motor transportable, however, there is nothing better in simplicity and effectiveness than Martin Harvey's idea.

The Harvey method has been devised in recognition of the fact that wheels are useful only in the actual moving of the set and that during the working of the motor they are just a nuisance. It consists in mounting the motor and control gear on, and across, two heavy baulks of timber so that the centre of gravity is near one end. Squares are cut in the under-side of each timber to locate a detachable square axle carrying two wheels, preferably rubber-tyred, and detachable handles are fitted. In this way one man—at most two—can wheel the outfit on any reasonably good surface. Having got the set approximately in position, the handle end is lifted until the other ends of the baulks rest on the ground and the chassis can be tilted clear of the axle, which is then removed and the chassis returned to rest on the ground, where it forms a firm base (Fig. 2).

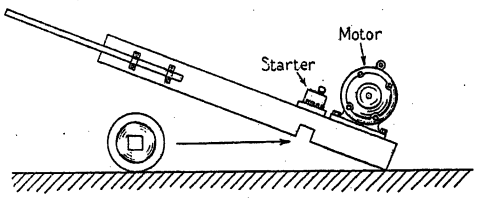


Fig. 2.—Harvey conversion chassis for transporting heavy farm motors.

(3.2) Cost of Working

It is not proposed to deal with the economics, either absolute or comparative, of electrical operation, but a reader not closely familiar with rural supply conditions will want to know the approximate cost per kWh of the various operations hereinafter mentioned. This, of course, varies in different supply areas, but the author is not aware of any farm tariff which does not allow an all-in average cost of 1½d. or less per kWh, including all charges, provided a reasonable use is made of the facilities available, to the extent, say, of 10–15s. per week in the form of revenue. Putting it another way, there are few, if any, rural areas in which there is not a two-part or equivalent tariff offering a running charge of 1d. or less per kWh; ¾d. per kWh is common and in some areas the rate is, or falls to, as low as ½d.

(4) SPECIFIC APPLICATIONS

In dealing with the specific applications of electricity to farming operations an obvious classification would be according to farming type. In the past, however, this has not been found to be simple, as there is so much overlapping of types. Classification here, therefore, is made on the basis of type of process.

(4.1) Food-Preparing Machinery

This is probably the most important and fundamental class of operation on the farm after the actual field operations. It covers the grinding, crushing and mixing operations which go to the preparation of the requisite rations for feeding the livestock on the farm. The amount to be handled will vary (according to the type of farm) from a few hundredweights a week to as many tons.

(4.1.1) **Grinding Mills.**

The main operation in the food-preparation class is the grinding of the whole grain into meal to be used as the basis of the ration. While the plate mill has given yeoman service in the past, and is still widely used, it can hardly be considered to be either an ideal engineering mechanism or, indeed, a really adequate machine for the job it is intended to do. It may be, indeed, that its drawbacks—limited range of grinding, trouble with plates, rule-of-thumb control—have contributed something towards the serious decline in farm grinding since 1918. Certainly with the revival of grinding the more progressive farmers are thinking in terms of the hammer mill, and, when supplies and circumstances permit, these are installed.

The hammer mill has several advantages over the plate mill.

being both a better engineering proposition and a more satisfactory grinding—perhaps, more correctly, disintegrating—machine. There have, however, been substantial obstacles in the way of extensive installation of hammer mills. Originally developed for drive by tractor, they are generally made in sizes requiring 15–20 h.p. to drive, and are expensive to buy; in pre-war days they cost upwards of £80. While smaller sizes have been made, down to 5 h.p. in one instance, they do not appear to have received much support. This is probably due to the fact that these mills were still operated on the lines of the older plate mills with a man standing by all the time, so that it behoved the farmer to have as high a rate of output as possible. While the high cost of the plant—a mill and motor very often cost as much as £150—deterred the majority of farmers from installing hammer mills, a sufficient number were being installed as to be, in many cases, embarrassing to supply undertakings, especially in war-time. The situation in single-phase areas was particularly difficult.

The position of the hammer mill for farm-feed grinding has, however, been radically altered as a result of initiative and activity on the part of the electrical industry itself. As a result of experimental research carried out by the E.R.A.,[4] with co-operation from the Oxford Agricultural Engineering Institute, Rothamsted, Reading University, the West of Scotland Agricultural College and the Midland Agricultural College, and with eventual support from the Ministry of Agriculture—but with strong opposition from the agricultural machinery industry—a hammer mill has been developed, and is now commercially available, which covers the whole range of farm grain-grinding requirements and has automatic, low-loaded and low-priced characteristics. It is driven by a 3-h.p. built-on motor, and automatic control is effected either on a quantity basis, for which a special automatic hopper is provided, or on a time basis, for which automatic time-control is used. The meal produced is blown by fan to receiving bins, from which it is taken as required. A high degree of flexibility of installation is afforded, and the machine has been found capable of meeting the grain-grinding requirements of any class of farm; it will not grind straw and grass. It is being installed widely on farms, from those grinding only some 4–5 cwt a week to others handling 3–4 tons (Figs. 3 and 4*).

* Shown as a lantern slide.

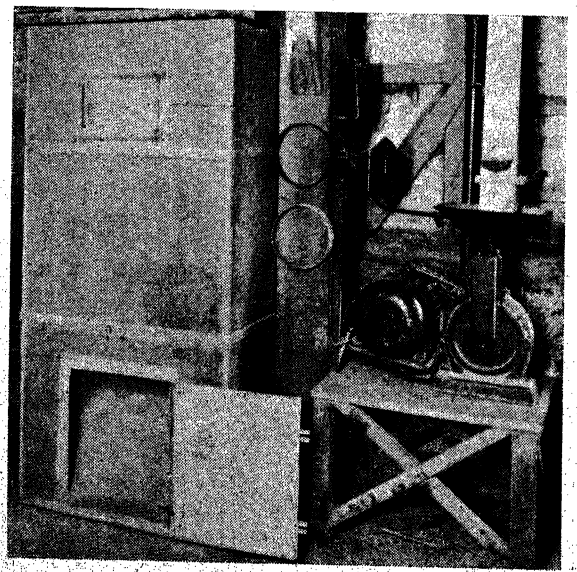
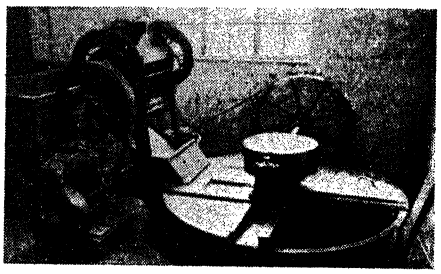


Fig. 3.—Automatic hammer mill and single-bin installation in Norfolk.

(4.1.2) **Mixing Machines.**

One of the most laborious manual processes is the mixing of the various ingredients—meal, minerals, broken cake—which go to make up the ration for feeding stock. The introduction of a mixing machine on a farm can be regarded as one of the best ways of applying Bomford's injunctions to "mechanize man."

There are two main types—the horizontal and the vertical (or geyser) type. The former consists of a metal vessel of trough-like shape with a horizontal shaft running its whole length and carrying skew-mounted blades. This is filled from the top, which is open, and emptied from a shutter-controlled opening in the bottom. The vertical type closely resembles a large oil drum with an open top but a bottom tapering to a shutter-controlled outlet. A vertical shaft, running from top to bottom



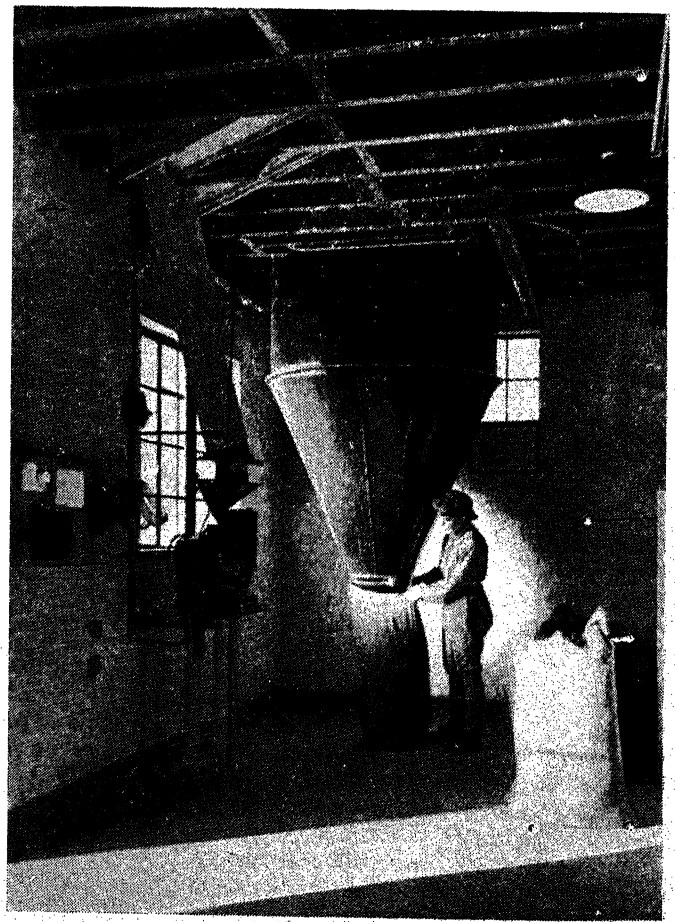


Fig. 5.—Composite view of food-preparing machinery at Rothamsted Farm.

Upper view: Top of mixer, showing direct-filling cake-breaker and opening for meal.
Lower view: Automatic hammer mill and draw-off from mixer.

of the chamber, carries an Archimedean screw along its entire length and of diameter equal to about one-third of that of the mixer. When the vertical mixer is full the rotating screw carries the meal upwards to cascade outwards into the body of the mixer again (Fig. 5). Vertical mixers can also be obtained for filling from the bottom.

Either type (horizontal or vertical) may be used for dry mixing, but for wet mixing, as with molasses, so common in the Lancashire poultry districts, the horizontal type is essential. Where the ingredients are fed from an upper floor so that the top of the mixer can be at floor level, either type is suitable, but where one floor only is available the vertical pattern fitted with a bottom loading device is of great advantage.

Mixers are rated by the weight of mix they will take at a time, and they vary from 1 cwt to 20 cwt capacity. Mixing takes from 10 to 20 min per operation. Power requirements vary from 2 to 20 h.p., the horizontal type requiring more power for the same capacity as the whole content is being moved at one time. A 10-cwt horizontal mixer will require 6 to 8 h.p., whilst the same size of vertical mixer will not need more than 4–5 h.p. For wet mixing, however, the power required for horizontal mixing has to be increased by 50–100%. Dry mixing uses 2–3 kWh/ton, and wet mixing 7–10 kWh/ton.

(4.1.3) **Layout of Food-Preparing Machinery.**

Much of the convenience of individual labour-saving machines can be lost if they are not suitably placed in relation to one another. Where the amount of food preparing is considerable, as for a large dairy herd, it is well worth giving this aspect some thought. It is not practicable, farms being as they are, to lay down any standard pattern, but J. R. Moffatt's placing of the food-preparing machinery at Rothamsted Farm might very well be taken as the basis of many new installations.

Fig. 5 is composed of photographs of the various constituent items, and Fig. 6 shows the layout diagrammatically. The upper floor has the grain hoppers feeding the automatic low-power hammer mill on the ground floor which blows the meal into storage bins on the upper floor again. The openings from these bins are so placed as to enable the meal to be easily measured into the top opening of the vertical mixer. At the same time cattle cake, stored on the upper floor, is weighed and broken direct into the mixer, other smaller ingredients are added and the mixed ration is drawn off into sacks on the ground floor, these being stored in ration bins ready to be wheeled away. The whole of this work is carried out by a girl. Individual drive through V-ropes is used for each machine, the cake-breaking being done by a 2-h.p. motor and the mixing by a 5-h.p. motor.

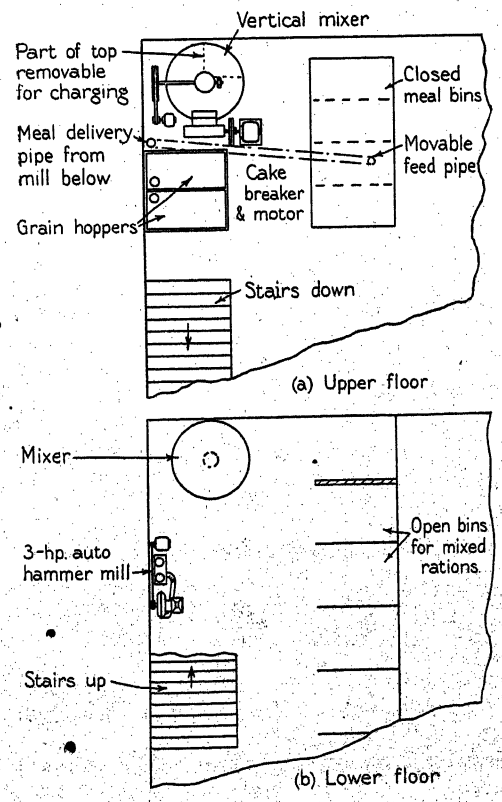


Fig. 6.—Layout of food-preparing machinery at Rothamsted Farm.

It still remains to make the Rothamsted layout fully mechanized by providing simple means for filling the grain hoppers from the main granary, and this problem is in hand.

Another instance of the ingenious arrangement of machinery to eliminate intermediate handling can be quoted from a large Mid-Cheshire dairy farm. Catering for a large dairy herd, the shippens have been fitted throughout with an overhead-rail transporter system. The "vehicles" are suspended from wheels running on the lower flanges of an I-section rail and consist of tilting trucks each holding about ½ ton. These are used for distributing to the individual stalls the various feeding-stuffs, including sliced roots and the chopped stems of kale and other greenstuff. Normally these would be cut by machine, delivered on to the floor and thence shovelled into the trucks, but the manual labour thus involved has been reduced by a dual arrangement of root-cutter and silage cutter feeding direct into the trucks, and shown diagrammatically in Fig. 7. To effect this the overhead rail has been extended from the shippen into a food-preparing room. Kale fed to the silage cutter is blown through the vertical pipe-line through the upper floor to a deflector which guides the chopped greenstuff into a truck hanging from the rail in the ground-floor room. Beside the silage cutter is a rotary root-cleaner which delivers the cleaned roots to a simple band-and-pocket elevator by which they are carried up to the floor above and delivered into an ordinary root-slicer, from which in turn the slicings are dropped through a chute to a second truck behind the truck receiving the kale choppings. In this way two men, each feeding one machine, can fill both trucks simultaneously in a few minutes and can then proceed to distribute. One 11-h.p. motor drives both machines, the bulk of the power being required for the silage cutter.

(4.2) Threshing

During the 1920's and 1930's when British arable farming was in the doldrums there was naturally a substantial drop in threshing. Indeed some of the grain-growing which did flourish involved combine-harvesting and so required no stationary threshing. The revival of grain-growing with the war led to a demand for threshers, but practically the whole of the output of threshing mills has been devoted to providing travelling threshers for co-operative and contract threshing. This means that there will be for many years a large—and probably ample—number of travelling machines available for the threshing requirements of the country. There has been, too, a remarkable growth in the use of combine-harvesters.

It would seem then that the prospect of any appreciable increase in the number of electrically-driven independent threshers is not bright. On the other hand, the author can vouch for a strong feeling of preference—especially by the younger farmers—for independence in the matter of threshing and attraction towards the idea of the completely mechanized and built-in plant. The deterrent factor is the high cost of the installation; and the nature of the electrical load involved does not make it economically attractive on a rural system.

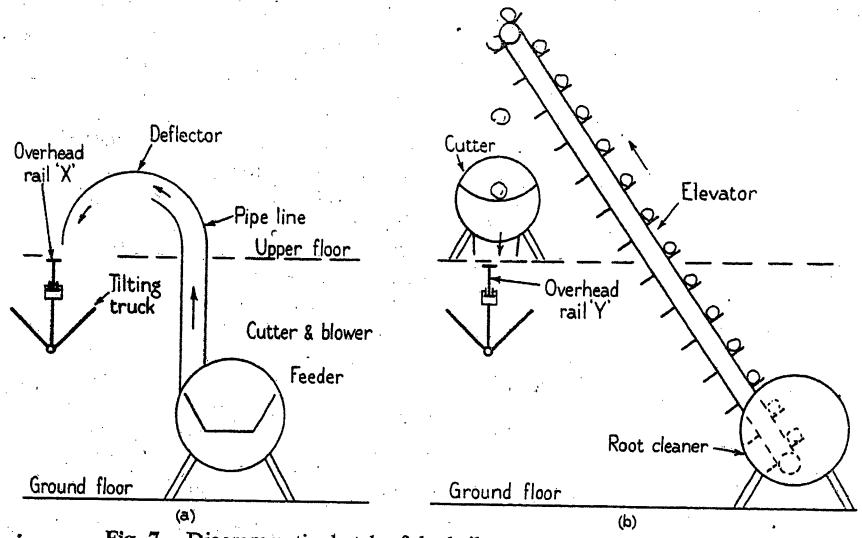


Fig. 7.—Diagrammatic sketch of dual silage cutter and blower (*a*) and root-cutter (*b*) installed on a Mid-Cheshire farm.
Imagine (*b*) just behind (*a*). Overhead rail Y is same as rail X but about 6 ft farther back.

There is, however, promise of a solution, more attractive to both farmer and supply engineer, on the basis of a much smaller thresher. Although hardly known outside certain restricted and comparatively local circles, there is available a range of small threshers with drums of 1 ft 6 in and upwards. With the exception of the smallest, which turns out roughly-sorted grain for use for stock-feeding only, they are available with complete sorting and cleaning apparatus turning out fully-graded samples. The power required is naturally lower, from 3 h.p. in the smallest and simplest to 12 h.p. in the fully-equipped 3-ft machine. Sufficient has been seen of these machines in action, some only partly mechanized, to justify a confident prediction that a 2-ft machine, fully mechanized on the delivery side, could be operated by two men or women, with perhaps an occasional third. The load, providing baling was not asked for, would be some 8 h.p. The price would be less than half of that of the full 4 ft 6 in machine, and there would probably be corresponding reductions in the cost of the whole equipment comprising the installation.

(4.3) Crop-Drying Plant

(4.3.1) Grain Drying.

The early developments in combine-harvesting in this country tended to reduce, by eliminating the threshing mill, a possible application of electricity, but later developments have been in the other direction. It is now realized that, for successful combining in this country, facilities must be provided for drying the grain after harvesting. Electricity is inherently and indisputably the most suitable source of motive power for running drying plants. Thus for a possible lost outlet for electricity in threshing—after all, travelling threshers might have been hired—there is a definite gain in type and value of load for drying. Moreover, the operational benefit gained by having electric power for drying is such that in obtaining the supply the farmer will go to considerable expense which he might not have considered otherwise.

The general requirements of a modern grain-drying plant are the removal of 5–6% moisture from grain immediately after combining. To this may be added, in practice, and in the more elaborate plant, temporary storing in "wet silos" before drying, storing in "dry silos" after drying, and re-circulation through the driers if the initial moisture content has been too high for complete reduction in one operation. This may often happen in the West and North where moisture contents of 25–30% are encountered as compared with the more usual 20–21% in the South and East. (The safe "dry" storing moisture content is 16% in bags and 14% in bulk.) Then provision has to be made for taking the grain to be cleaned and bagged-off for transport. All this can change a basically simple process—and, indeed, machine—into a most complicated and expensive layout.

The basic process is simply the blowing of heated air, and, later, cold air, through a layer of grain. If the various extras are not added, all the machines on the market can be run in this basic form. A few farmers have started operating in this simple way, but sooner or later they feel the need of a post-drying grain cleaner and sorter and this is added. Thus the basic practical farm-drying plant consists of the basic drier plus cleaner and an elevator for loading.

Heating is generally provided by very simple—indeed crude—coke furnaces, the combustion gases being mixed with cold air to reduce the temperature and then blown through the grain. In some plants crude-oil burners are used, the combustion gases again being used.

There are two main types of drier—the vertical type and the horizontal type.

(4.3.1.1) *Vertical Driers.*

The general principle of the vertical drier is the provision of a vertical "wall" of grain, some 4 to 6 in thick, which moves steadily downwards by gravity from a feeding point at the top to be emptied at the bottom; during its passage first hot air, and finally cold air, is blown through the grain.

The leading makes of vertical drier, with their main characteristics, are: the Turner–Oxford, in which the grain forms two parallel walls on opposite sides of a rectangular central space, the ends being closed up by solid sheeting; the Kennedy and Kemp and the Mather and Platt are similar; the Montgomery Lecoche has the wall of grain in the form of a cylinder, encircling the central space; in the Porteous the central space is square in plan, being enclosed by four grain-walls; the Goodall is of a circular type but the actual grain chamber is enclosed by concentric cones, the lower pair being inverted and the base of the upper pair resting on the inverted base of the lower. Other distinctive features are that while the grain is elevated mechanically in the others, it is done pneumatically in the Kennedy and Kemp; this takes rather more power but affords simplicity and flexibility. Again, in the Goodall drier the cooling is done in a separate section to which the grain is elevated from the hot section. Vertical driers take up comparatively little ground space and lend themselves to operation in banks in centralized drying stations (Fig. 8*).

The capacity of these machines for a 6% extraction is 2–3 tons/hour, except the Mather and Platt which puts out 1 ton/hour. The power requirements are roughly 6 h.p./ton/hour. These figures cater for driving the cleaner, although this is sometimes done by a separate 2-h.p. motor. Where special auxiliary elevators and conveyors are fitted, the power requirements may well be raised by as much as 5 h.p. The consumption of electricity appears to vary from 6 to 10 kWh/ton dried (at 6% extraction), depending on whether the machine is run at or below capacity and on the elaboration of equipment.

* Shown as a lantern slide.

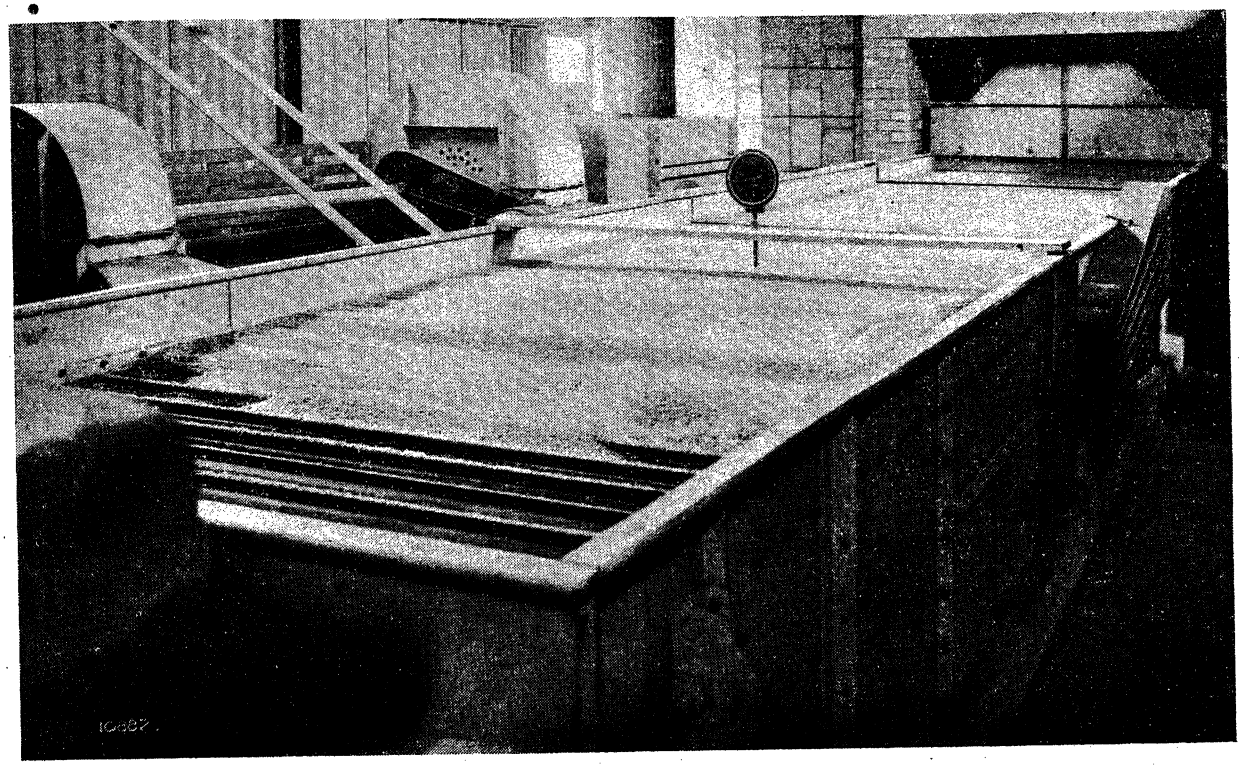


Fig. 9.—Horizontal grain-drier—conveyor type.

(4.3.1.2) *Horizontal Driers.*

In the horizontal driers the hot and cold air in turn is blown upwards through a layer of grain lying on sheets of perforated metal. In one type—the Ransomes-Davies conveyor drier—the layer of grain is kept moving forward over the perforated bottom by means of a scraper-conveyor, the process thus being continuous (Fig. 9).

In the other of the two well-known horizontal driers—the I.C.I.—the tray or batch principle is used. This drier is really a grass-drier, but by replacing the large-mesh bottom sheets in the trays by smaller-mesh sheets, grain can be dried. The process proceeds in batches, grain being laid over the mesh bottom to a depth of several inches; then hot, and later cold, air is blown up through the grain. Generally the trays have to be filled and emptied by manual labour, but it is now possible to fit a device whereby the dried grain can be run or swept out into a pneumatic pipe-line whereby it is blown where required. While one set of trays is being dried, the other is being emptied and then refilled (Fig. 10*).

The horizontal-conveyor type, not utilizing gravity for moving the grain through the drier, requires rather more power than the corresponding vertical types, the plant described requiring 15–20 h.p. and the output being about 2 tons/hour. The tray type requires some 15 h.p. for fan only; the output is of the order of 2–2½ tons/hour.

(4.3.1.3) *Drying in Sheaf.*

The general situation in regard to crop-drying has been somewhat obscured by the publicity given to grain drying, in connection with combining. A large section of the farming community, however, is more concerned with the problem of drying the corn in sheaf in order to get it to the threshing stage. Small Scottish farms, in the North-West in particular, and the hilly district farms in England, are interested in this aspect, which has received practically no attention. It may then be well to draw attention to the fact that a sheaf drier has been developed and has been in use in Yorkshire for some years.[5, 6] This makes provision for building the sheaves in the form of a stack round an inner cone consisting of iron piping. A coal-fired boiler circulates steam through these pipes, while air is blown by means of a fan into this inner space and thence over the heated pipes and out through the sheaves.

(4.3.2) **Grass Drying.**

The other major problem in farm drying is the handling of the grass crops to eliminate the uncertainties of haymaking. Efforts in this direction started with attempts to "make hay" and finished in the development of an intensive process of repeated cuttings of short grass to be dried and made into a high-protein meal. Nowadays a compromise is generally effected, an early cutting being made for short-grass drying, the main crop being treated as hay in the usual way and the residue, if any, being dried. The artificially-dried grass is either ground into meal or compressed into bales.

Grass-drying plants generally work on the horizontal principle, although a rotary type is sometimes used. Since good grass-growing districts are not good combining districts, grass- and grain-drying do not often overlap and the question of dual-purpose machines does not often arise. Those grain driers of the tray type and of the horizontal conveyor type (see Section 4.3.1.2) can be used for both purposes. The former is probably rather more satisfactory as a dual-purpose machine. There are other horizontal types of grass drier, but these are not suitable for grain drying. Grass can also be dried on the stack system (see Section 4.3.1.3).

As grass is generally wetter than grain, drying is more expensive and in practice slower; a simple system of regenerative heating is commonly used. A common rate of output is some 3 cwt of dried grass per hour. The power requirements for the most normal conveyor type are about 15 h.p. for fans, conveyor and elevator, and a further 20 h.p. or so if the grass is to be ground

* Shown as a lantern slide.

into meal, or about 3 h.p. if it is baled. The power consumption for drying only is of the order of 80–90 kWh/ton dried. Grinding accounts for nearly as much in addition, but baling requires only some 5–6 kWh/ton.

(4.3.3) **All-Electric Driers.**

The question of making drying all-electric by using electrical heating has been raised from time to time, but it has never been possible to give an encouraging answer. The hard facts are that electricity has to compete with coke used in a crude, simple and, because of the use of combustion gases, comparatively efficient form. Nevertheless many farmers—technically-minded farmers appreciative of the position—have expressed strongly their ambition to have all-electric operation, even to the extent of paying basically much more than they do now. They have in mind, not only freedom from furnaces and their attendant troubles, and the simplification in labour which might ensue, but the fact that with the really effective temperature control so afforded the plant could be run at optimum temperatures without danger of overheating the grain. In addition there would be the elimination of damage to fittings and structure resulting from the emission of combustion gases into the drying room.

The first and somewhat courageous step in all-electric operation has been taken by the Bedford Corporation in conjunction with a local farmer at Haynes, Bedfordshire, in converting a Kennedy and Kemp drier to electrical heating with a connected load of 182 kVA. So far the experience gained with the plant has completely satisfied the farmer (Fig. 11*).

It is, however, unlikely that any substantial advance in all-electric operation will take place on the lines of straight conversion of existing large plant. After all, how many rural suppliers would welcome individual loads of this order? It will more probably come in the form of smaller plants, with some 50 kVA of connected load, running fully automatically night and day, possibly using regenerative heating in some form or other.

Experiments in all-electric grass-drying have been carried in Switzerland to the state of commercial application[7] in the form of a recuperative-type conveyor machine. The fundamental principle of the method of recuperation employed is that the water eliminated from the first stage in the form of vapour is not allowed to escape to the atmosphere, as has hitherto been the case, but is condensed in a heat exchanger so that the heat of evaporation is utilized to assist the further drying process. The normal evaporation from grass driers is some 2 000 B.Th.U./lb of water evaporated,[8] whereas the Brown-Boveri method requires only some 1 150 B.Th.U./lb.

(4.3.4) **Hop-Drying.**

The drying of hops after picking is a highly specialized and localized farming process. It is traditionally associated with Kent, but it is probably true to say that the Herefordshire and Worcestershire hop farms are more advanced in the modern methods of drying. Nevertheless, even there the process is fundamentally crude, consisting as it does of placing hops on a hessian-covered and slatted upper floor of the kiln or oast, warm air being blown into the lower chamber and thence passing through the hops for hours at a time. As this goes on with successive refillings and emptyings for a month on end, it seems strange that some form of continuous process has not been perfected long ago. Something of this nature has been done in Germany, but there is no sign of its adoption in this country. With the crude conditions of heating presented, electricity has not competed so far in this respect, coal- and oil-firing being usual. With the practically continuous running required, electricity is the obvious—and almost the universal—means of providing motive power for the fans—some 5 h.p. per kiln—and for the automatic stokers—¾ h.p. each—when used. In at least one case the farmer has used his hop-drying kiln for drying grass.

* Shown as a lantern slide.

(4.4) Milk Production

The advantages of electricity over all other forms of energy for use in connection with milk production and handling are so evident that nowadays they are never questioned. The degree to which it is used, when available, is governed by economics, or rather by the individual farmer's interpretation of economics. In a large—and increasing—number of cases the milk-producing plant is all-electric, even to the heating of water and raising of steam. The main requirement in milk production—hygiene—is so dependent on adequate lighting for its achievement that, for this, electricity is almost a *sine qua non*.

(4.4.1) **Power.**

(4.4.1.1) *Milking.*

It is no longer a question as to whether machine milking is satisfactory, but as to how best to ensure the most hygienic handling of the equipment. The fine points of dispute on the principle have not survived the conditions imposed by the war, and machine milking is expanding at a rate limited only by supplies of materials.

Practically all milking plant is now operated on the suction principle, and the energizing unit is a suction pump driven by a motor of 1–2 h.p. The consumption is of the order of 30 kWh per cow per year for two daily milkings, increasing, but not proportionately, where three milkings per day is the practice.

(4.4.1.2) *Cooling.*

Only in very rare instances is the water supply available throughout the year at a temperature sufficiently low to achieve really effective cooling, and it may be taken—and is now realized in official circles—that the bulk of the milk produced on farms in this country is, at some time or other, insufficiently cooled. Also, where mains water is available and used, the consumption for this purpose is sometimes not only embarrassing to the water undertaking but expensive to the farmer.

Everything points to a tremendous expansion in the installation of farm cooling-plants sooner or later—it may come suddenly under official direction. Since electrical operation is the only means worth practical consideration for a small farm cooling-plant, more extensive installation will follow increasing rural electricity supplies; it will also follow a reduction in the cost of plant, which will come only when some manufacturer is courageous enough to embark on a real programme of production. The usual mechanical milk-cooling plant takes the form of a dual type, partly cooled by water and partly by refrigerant. More attention should be given to the elimination of the water stage and to the complete cooling by refrigerant. The annual consumption for dual cooling is of the order of 20–30 kWh/cow, and the use of full cooling by refrigerant would roughly double this; even this would not be serious at the running costs now available on farm tariffs.

In the simplest forms of cooling plant, where no milk is held on the farm, a direct-expansion plant is used to supply refrigerant direct to the cooler; the motor required for this purpose varies from ¾ to 2 h.p., depending on the capacity of the cooler. This type of cooler must be sterilized *in situ*, and this is effected by fitting it with a metal jacket and connecting it to a steam line.

Where milk is to be held a cold-chamber is required and it is, perhaps, simpler to use the brine-tank system, re-circulating the brine by pump to the milk-cooler. In this type the cooler can be removed and placed in the general sterilizing chest, thus, in many cases, simplifying the sterilizing arrangements.

(4.4.2) **Heat.**

The main expenditure of energy in milk production and handling is for heat—water has to be heated for washing and steam raised for sterilizing—and this offers one of the biggest and best outlets for electricity on farms. Farms with herds of 20–40 cows can account for 5 000–10 000 kWh/annum for dairy heat alone.

(4.4.2.1) *Self-contained Chests.*

Where all the utensils to be sterilized can be detached the simplest, and possibly soundest, proposition is a self-contained chest with a built-in boiler heated by immersion units, the steam being delivered straight into the chest. These are available in loadings of from 4 to 9 kW, depending on the size of chest. This type of plant has given yeoman service in all parts of the country, but, strangely enough, there still lingers in certain, but now limited, official county circles a prejudice against these self-contained chests because apparently they do not generate steam "under pressure." It can be said, quite definitely and categorically, that a chest of reputable make will do all that is expected of it; that is, it will sterilize all the utensils and appliances put inside it. Furthermore, it is now possible to have chests with a nozzle attachment which allows small tubular parts, such as those used in milking machines, to be blown through, and even permits the use of a churn stool, whereby larger utensils such as churns can be sterilized outside the chest. In certain makes it is also possible to use this extra steam circuit to blow steam into a tub of cold water and so heat it up for washing; generally, however, it is more useful to have hot water "on tap" from a separate storage heater, particularly where a special thermostatic heating tariff is available.

These self-contained chest units have come to be known generally, though loosely, as "electric sterilizers." They have a particular appeal to the small farmer who may be modernizing his plant, or to the newcomer, since they require no more space than any chest would take, require no boiler space and, of course, no separate boiler room which has to be provided with coal firing (Fig. 12*).

(4.4.2.2) *Steam-Raisers.*

Where a good chest already exists, or where steam pipe-lines are to be used for sterilizing coolers, elaborate milking equipment, etc., in position, it is necessary to have a separate steam-raiser with a higher evaporative capacity. The question of pressure in farm dairy sterilizing has been something of a bogy, and pressures of 50 and 60 lb/in^2 have often been asked for, apparently with no particular evidence of need. The truth is that very little is definitely known about the exact steaming requirements for different conditions. It is indeed doubtful whether a pressure of 10 lb/in^2 need ever be exceeded, or indeed whether anything beyond 5 lb/in^2 is required for the vast majority of pipe-line installations.

It is almost essential, however, where an electrical steam-raiser is being used to supply an existing chest, that the latter should be insulated on the top and all sides; this also applies, where practicable, to the steam pipe-line.

Steam-raisers are of two main types, those with immersion heaters and the electrode type. The loading of the immersion-heater types ranges from 9 to 15 kW and, subject to de-scaling in hard-water districts, they operate satisfactorily, the main criticism being of petty idiosyncrasies on the part of individual makers. They can, of course, be a source of uneasiness if no provision is made for automatic disconnection of the heating elements if the water supply fails.

The electrode type with loadings up to 20 kW has given satisfactory results, the main disadvantage being the variations in loading with different water conditions. It also requires frequent servicing in hard-water areas.

There is, to be frank, no royal road of "fit and forget" about electrical steam-raisers, or indeed about electrical chests. They should receive regular inspection, and being of vital importance to the farmer and good revenue-producers to the supply undertaking, they are worthy of having mutually satisfactory servicing arranged. Those areas in which there are fewest complaints about sterilizers are those in which service arrangements have been made.

To the rural supply engineer who is uneasy about 15-kW or even 9-kW sterilizers on his mains, there is a prospect of definite load alleviation after the war. The Americans have been developing the principle of low-loaded storage steam-raisers—a principle once tried tentatively and abandoned by the North-Eastern Electric Power Co., and these are now in production in the U.S.A. This has enabled the requirements of a medium cow herd of, say, 40 cows to be met with a connected load of 1½ kW and of a large herd by no more than some 3 kW. This principle is almost certain to be adopted in this country in due course.

(4.4.2.3) *Pasteurizing.*

The subjection of the raw milk to pasteurization, or some other form of heat treatment whereby it is held at certain indicated temperatures for appropriate times, has been the only basis on which milk can be handled in large quantities, and is therefore largely practised by the large-scale distributors. Government legislation now pending, however, promises to make pasteurization compulsory, with the alternative of providing tuberculin-tested (T.T.) herds, as a counter to the danger of tubercular infection from milk. As it is difficult to imagine that more than a small fraction of the milk-producing herds of this country will comply with the T.T. requirements for many years to come, a wide spread of pasteurization is to be expected.

Pasteurization is a straightforward and comparatively crude application of heat and, having been done almost exclusively in large plants, process steam has been available there for the purpose and electricity has not generally been considered practicable. Americans have, however, produced electrically-heated pasteurizing units, mainly on the electrode principle, using the milk itself as the conductor. There is, however, no evidence of any substantial demand for them, or that they have been installed for other than their advertising value.

Nevertheless the possibility of pasteurizing being carried out in much smaller plants than hitherto, where ample steam may not be available, opens the way to a reconsideration of the electrical method in small units. Nothing more can be said at the moment, but it is as well to indicate that this problem is not being overlooked.

(4.4.3) **Lighting.**

The conditions on farms, and even on corresponding parts of farms, vary so much that it is impossible to lay down any hard-and-fast rules in regard to lighting. Indeed there are no rules other than the basic one of providing adequate intensity of illumination. While it is unlikely that the personnel responsible for lighting cowhouses will generally have the facilities for testing this, some 3–4 foot-candles should be aimed at. Otherwise it is mainly a matter of common sense to achieve reasonably good lighting.

Nevertheless there are many instances of apparent failure to exercise any discrimination whatsoever in lighting. This applies both to milk-handling rooms, where brilliant lighting is justified and where the conditions are straightforward, and to the cowhouse or the milking house itself, where a lower intensity is called for but where the conditions are rather different from those

* Shown as a lantern slide.

usually encountered by an electrician. There are however certain general considerations which, if complied with, will ensure satisfactory illumination of the cow-house.

(*a*) The udders of the cows must be illuminated, so that comparatively low-angle lighting should be provided.

(*b*) Pools of light should be avoided, and the temptation to skimp the lighting points must be resisted—one light per 4-cow run is probably a minimum.

(*c*) Some light—even if diffused—should be allowed to reach the upper parts and ceiling of the milking house. To work in a tunnel of light with deep gloom overhead is very depressing; simple lighting units are available which prevent this.

(*d*) With some types of cow-stalls and fittings the central lighting will not illuminate the feeding trough or the feeding gangway; extra points should be provided for this purpose.

(4.4.4) **Centralized Milking.**

A significant trend in mechanized milking and milk-handling is the development of the centralized milking room or "milking parlour" as it is sometimes—somewhat unhappily—called. Whereas in normal milking practice the milking-machine suction line is run throughout the cowsheds and milking is carried out *in situ*, centralized milking utilizes a special milking room with only a few stalls, say one to every five cows, to which the cows are led in turn for milking. This means that instead of having to exercise maximum hygienic precautions over a large area, and perhaps a number of buildings, these can be concentrated in a comparatively small area. The cows can *live* very happily under conditions which would be inimical to high-grade *milking*, and they can even live out of doors. This development is of very great help to a small farmer whose output is expanding, or to a man with existing and old-fashioned buildings who is trying to improve his standards of milking.

While the centralized-milking idea would have achieved something even if it merely centralized the normal milking procedure, in actual practice it does much more than this. Instead of the milk having to be emptied from the milking unit into a bucket and then carried to the cooler—the normal milking practice—it is usual in the centralized plant for the milk to be drawn from the cow to a central point where it is automatically released to go through the cooler and thence to the bottles or churns without any intermediate handling; this is known as the auto-release system. Provision can also be made for the output from each cow to be weighed and recorded on its way to the releaser; this is referred to as auto-recording (Fig. 13).

There is much in these systems, particularly in a country such as ours where the general standards of milk and milking are generally somewhat poor, to give the progressive farmer conscientious ideas about his own milk production. The principle can be applied on quite a modest scale and with none of the elaboration and showmanship which have appeared in one or two installations and which may have discouraged practical farmers: centralized-milking units have been installed for herds as small as 15 cows.

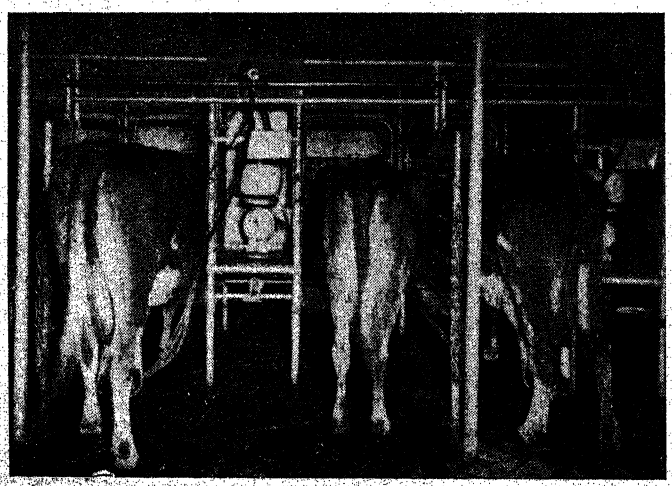


Fig. 13.—Auto-recorder-releaser milking system.

It is not, however, certain that the basic idea is always applied in the best way, in relation to the post-milking processes, or that sufficient thought is always given to the planning of the auxiliary equipment. Ideas differ, but the author feels that some useful purpose might be served by reproducing here a layout suggested by Martin Harvey, to whom he is indebted for the information and plan. Fig. 14 shows a suggested all-electric milkhouse, and, for fuller information, the adjoining milking-room (as laid out in the area served by the Shropshire, Worcestershire and Staffordshire Electric Power Co.). The milk-house is fully equipped, but is not provided with elaborations such as pasteurizers, milk-capping machines or can-washing machines. It is intended rather to provide the conditions required by a producer-retailer maintaining a high-class business in a local town, and provides for a herd of 80–100 cows. The scale can be reduced or expanded to suit varying circumstances. As it stands, one of the milking sides can be run independently. The main feature of the milk-house is the one-way flow principle from "dirty" cans to "clean" room; no one need come from the "dirty" room into the "clean" room without first washing and changing overalls in the staff room.

(4.5) Special Applications

(4.5.1) **Hoisting and Elevating.**

As has already been remarked, the amount of manual lifting and trundling which goes on at a farm, and which is apparently quite complacently submitted to, is astonishing. This complacency is gradually being somewhat shaken as more girls are employed, and even where the men find that the extra time taken up makes their job harder. Particularly noteworthy is the comparative rarity of even a hand-operated hoist, and the still rarer fitting of a power-operated hoist. The layout of farms in this country, too, generally calls for much horizontal transportation. In distinct contrast is the latest Swedish practice. There the new barns are several storeys high, and all crops—hay, grain (threshed and unthreshed), roots, etc.—are power-hoisted to one or other of the upper floors. All subsequent movement is downwards by gravity, culminating in the feeding troughs of the animals, which are kept on the ground floor.

Most farms in this country, however, provide one upper floor, from which grain is taken for storage and subsequent gravity feed to the grinding mill below. This grain is generally handled in sacks, and the use of a power-operated sack-hoist can avoid much hard work and save much time. Apart from some locally-made and home-adapted plants, the most generally used type is the friction-controlled winch. This is a very robust machine and one simple to control; the motor—1 to 2 h.p.—runs continuously, and lifting, stopping and lowering are controlled by a rope which, depending on the pull exerted, lowers, lifts or brakes through a combination of friction pulleys and eccentrically-mounted shaft.

This type of hoist is a considerable advance on carrying sacks upstairs or hoisting them by hand. It does, however, still leave the sacks to be wheeled or carried to their final destination on the upper floor. Practically no use seems to be made on farms in this country of the self-contained, transporting hoist frequently used on the Continent. Fig. 15 shows one of the few installed

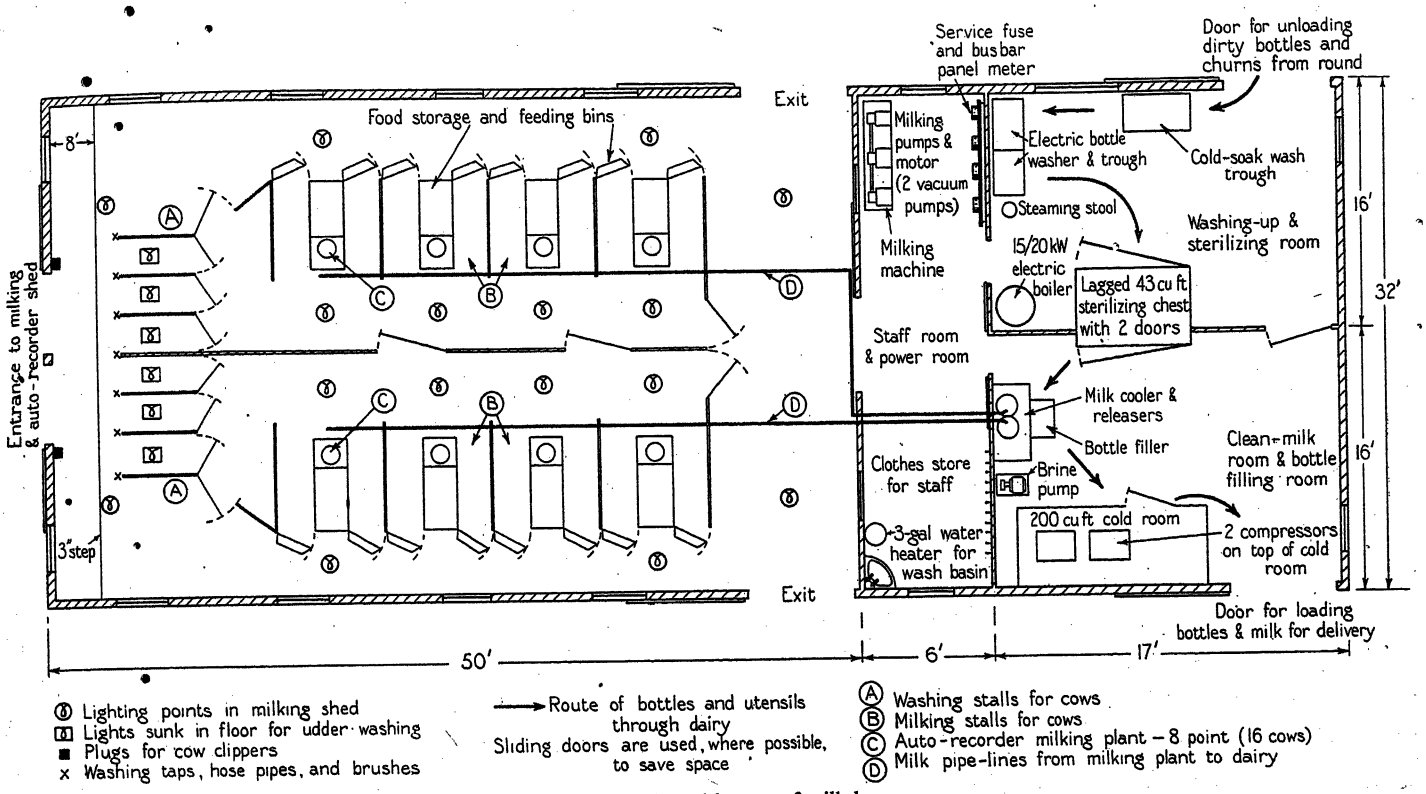


Fig. 14.—Suggested layout of milk-house.

on farms in this country, in this instance on a North-Eastern farm, although it is not actually of the transporting pattern. These self-contained units are driven by a ¾-h.p. motor.

Those farms possessing a horizontal mixer can have the extended low-speed shaft fitted with a winch-drum, so that if the mixer is suitably situated this can be used to operate as a hoisting

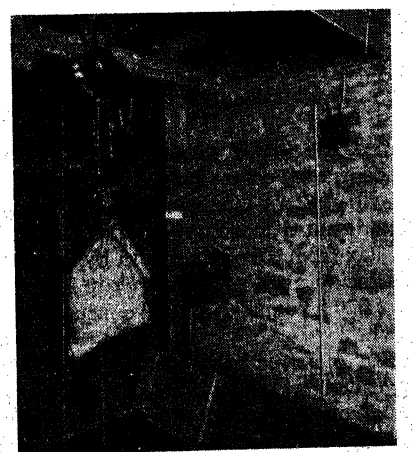


Fig. 15.—Self-contained electric hoist in action.

winch. This is a convenient way of carrying out relatively infrequent hoists but is not so convenient as the separate hoist for regular work.

In many cases the grain is to be, or can be, stored in bulk so that its transport upstairs in sacks is only a means to an end. Here, it would be simpler and more economical in labour to tip the sacks into a hopper on the ground floor and let the grain be lifted mechanically, straight into the upstairs bins. This could be achieved by mechanical cup elevators and scraper-conveyors, but this system becomes complicated and expensive except on short, simple runs. Far too little attention is paid in the agricultural world to the possibilities of pneumatic elevation and transport of grain, which provides much more flexibility and freedom in layout and is likely to be less expensive to install.

The best use of pneumatic elevation is to lift the grain to the highest point available and then to deliver it by gravity to the exact point at which it is required. There are two methods which avoid passing the grain through a fan and thus bruising

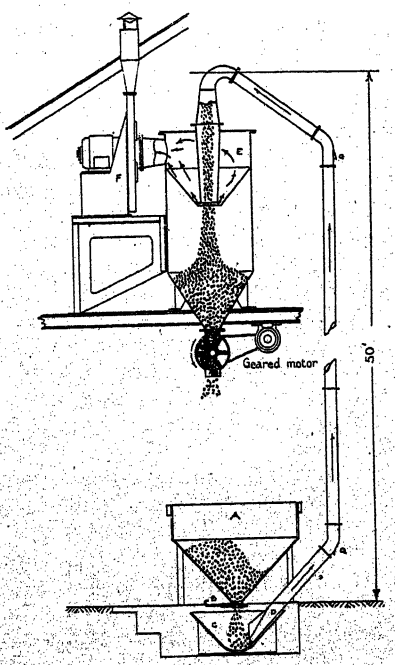


Fig. 16.—Diagram of suction-release method of grain elevation.

or breaking it. In the first—a positive method—air can be blown into a pipe line which, picking up the grain on the way, will carry it to the required point, there releasing it through a cyclone. Another method, not so well known, is the suction-release system, whereby air is sucked into an expansion chamber at the highest point, carrying the grain with it in suspension. When the air-cum-grain mixture enters the expansion chamber the air velocity is reduced and this allows the grain to fall to the bottom of the chamber. A small auxiliary motor drives a releaser whereby the grain is released without breaking the suction. The Drummond method of utilizing this idea, as applied to a mill in Hertfordshire, is illustrated diagrammatically in Fig. 16. The capacity of this plant is 3 tons/hour, when operated by a 6½-h.p. motor. This principle might well prove to be highly useful on farms.

(4.5.2) **Water Supply.**

There is much heart-burning in rural welfare circles about supplies of water in rural areas, and there is a tendency, fostered apparently in official quarters, to consider that widespread water mains are essential. In actual fact, in many parts of the country there are ample supplies available locally from springs or from wells at no excessive depth, and where electricity is available this can be so handled as to afford by automatic operation the full convenience of the water main.

Electricity has been found to provide for farm purposes not only an ample water supply but also an ample water service, of adequate pressure and automatic operation, the cost being—in the author's experience, without exception—lower than that from the corresponding mains service; a common figure, and by no means a maximum figure, for mains supply is 2s. per 1 000 gallons, where only in exceptional cases will the total cost of that from an electrical installation approach half his figure. Indeed it is no uncommon thing for a farmer to install both independent and mains supply, retaining the latter as a standby only.

Automatic operation can be achieved either by a gravity tank system, controlled by a float switch, or by the pressure-tank system. As adequate pressure is, however, highly desirable, particularly in large modern dairy installations, the balance is in favour of the pressure-tank system, where pressures of 40–50 lb/in^2 or upwards can be obtained. To provide even half this pressure on the gravity system would require a tank to be at a height of 40–50 ft, which would be unsightly and costly and difficult to provide in war time (Fig. 17).

A drawback to the pressure-tank system is the lack of any reserve in the event of a breakdown of either pump or supply, and, because of this fear, which is justifiable on a dairy farm, a gravity system is often preferred. Since failure of supply is very rare—and very short in duration—and plant failure is the main potential danger, it might often be cheaper and better to install a pressure tank with a standby pump and motor. The alternative—probably the best on all counts—is the duplex system as used at Reading University Farm, where a low-level gravity tank, acting as the main reserve, feeds a pressure-tank system, which can in turn be by-passed in the event of a supply failure or plant breakdown.

The most interesting development in recent years has been the production of submersible pumps in small sizes suitable for supplying individual farms. They offer for deep-well work a simple type of installation (Fig. 18*) which has been very reliable indeed. Some very cautious engineers prefer to have a second string to their bow in the event of electrical failure, and for deep-well work fit the rod-and-plunger type of pump. This type, with the driving gear at the top, certainly offers the opportunity of arranging emergency alternative drive from a small engine (if available). There are excellent examples of this type of pump, in particular those with withdrawable plunger and valves which facilitate maintenance.

* Shown as a lantern slide.

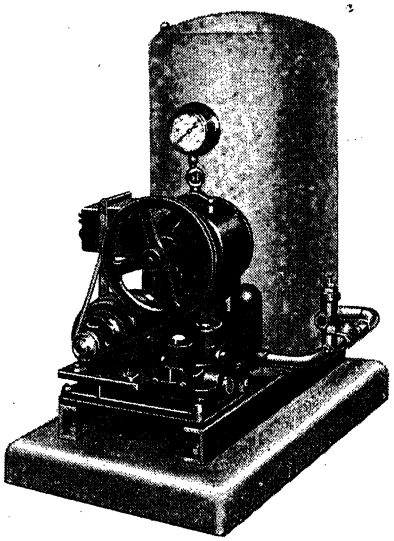


Fig. 17.—Small automatic pressure-tank pumping set.

(5) CONCLUSION

The author has confined the scope of the paper to what may well be defined as general farming—the arable, the dairy and the mixed farm. He has had to resist the temptation to touch upon the many other, but more specialized, branches of agriculture in the widest sense—poultry-farming, fruit-growing and market-gardening. Each of these has wide and interesting scope for electrical application and discussion, but to include them would be to reduce the paper to catalogue form.

The author has not forgotten the various interesting but highly specialized individual plants which offer good electrical loads in certain localities, for example the hop-picking plants in Worcestershire, Herefordshire and Kent, and the pea-picking plants in Lincolnshire.

There are, too, the highly productive and specialized rural factory plants depending on the local farms to keep them going, exemplified by an Eastern Counties flax factory with 500 kVA installed load and annual consumption of 473 000 kWh, handling 10 000 tons of flax from 5 000 acres, and by the Navenby (Lincs) grass-meal producing plant of British Crop Driers, with a connected load of 1 000 h.p. and an annual consumption of the order of 1 million kWh.

The author has preferred to restrict his field of survey and to treat the subject with two aims in mind. He recognizes that a large number of engineers and others are interested in rural electrification and yet have no opportunity of obtaining practical knowledge of the subject. He has endeavoured to present to these a broad picture of the subject. At the same time there are engineers who are actively engaged in applying their knowledge and skill to farm electrification but who, for various reasons, have no opportunity of visiting other areas and seeing what is happening there. For these the author has endeavoured to afford a clearing-house for modern ideas on the subject and to present a general background against which local trends can be measured.

Finally he makes no claim to completeness in the survey, being for various reasons in touch with but a small part of the total field covered. He therefore invites, and would welcome, any

information on special aspects of farm electrification; that these may have but local interest or be in crude form is immaterial, as many a simple idea, developed for local expediency, contains the germ of a process of widespread application.

(6) ACKNOWLEDGMENTS

In the matter of expressing his indebtedness for help and assistance given towards the preparation of this paper, the author is in some difficulty. While much of the material on which the paper is based is the result of years of contact with those engaged in rural electrification, it has been brought up to date by visits to and discussions with the leaders of rural electrification in this country. It would, however, be impracticable to mention by name all the individuals who so willingly, and often at great trouble to themselves, gave of their time and experience, but the author would like to place on record his appreciation of the enthusiasm he found amongst those engaged on rural electrification work, and of the willingness and open-mindedness with which they both gave and accepted information, suggestions and ideas.

He therefore proposes to restrict formal expressions of acknowledgment to mention of those undertakings which have more recently been consulted and which so readily gave the services of various members of their staffs: Bedford Electricity Undertaking; Boston and District Electric Supply Co., Ltd.; Chester Corporation Electricity Dept.; Derbyshire and Nottinghamshire Electric Power Co.; Dumfries County Council Electricity Dept.; East Anglian Electricity Supply Co.; Mid-Cheshire Electricity Supply Co., Ltd.; Mid-Lincolnshire Electric Supply Co., Ltd.; North-Eastern Electric Supply Co.; Northmet Power Co.; Norwich Corporation Electricity Dept.; Northampton Electric Light and Power Co., Ltd.; Shropshire, Worcestershire and Staffordshire Electric Power Co.; Wessex Electricity Co.

The author also wishes to thank the following for supplying the photographs from which certain of the illustrations were prepared:—

Drummond Patents (Holdings) Ltd.—Fig. 16; Gascoignes (Reading) Ltd.—Fig. 13; H. J. Godwin, Ltd.—Fig. 17; North-Eastern Electric Supply Co.—Figs. 1 and 15; Norwich Corporation Electricity Department—Fig. 3; Ransomes, Sims and Jefferies, Ltd.—Fig. 10; and The Director, Rothamsted Experimental Station—Fig. 5.

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DISCUSSION BEFORE THE INSTALLATIONS SECTION, 13TH APRIL, 1944

Mr. J. C. Leslie: I feel sure you would like me to thank the author for the very interesting survey which he has given us of the application of electricity to the farm. The farmers' organization which I represent here is most anxious to see that in the future electricity is given the widest possible and most economic use in our industry.

The author refers in the early part of his paper to the cost of installation and to general running costs, and suggests that to-day these are perhaps no longer a material consideration. That is too rosy a picture to paint, even now. The farmer to be up to date must have access to the same services as other industries, and particularly those industries in urban areas. Will the critic of agriculture allow the farmer to receive electricity and other services at costs comparable to those which his own urban industry is called upon to pay? Unless those who are prepared to criticize the alleged lack of efficiency in the agricultural industry, are at the same time prepared to see that it is supplied with the tools it needs at the same rates as those which apply to other industries, criticism on that score cannot be justified. The cost of obtaining a supply of electricity is a matter which is very much in the minds of farmers to-day.

Farming is made up of a very large number of small enterprises, each of about 100 acres. The principal consumers of electricity in the future will therefore be the small family farms. I agree with the author that the electrical industry must consider the application of electricity to large-scale enterprises, such as grain-drying, threshing, soil sterilization and even field cultivation; but we as an organization are not particularly interested in developments of that kind, because they have no general application to the industry. In what directions is a general application feasible? Most farm implements are used for only a very limited number of days in the year, and we cannot afford to have an electric motor standing idle for 300 days out of 365; that would be unthinkable in any enterprise which has to be run for profit. We must therefore consider the application of electricity to machines which are in constant daily use.

The first use of electricity is in the farmhouse itself. If we could persuade the farmer's wife that electricity is a big labour-saver and a saver of money, we might go a long way towards getting the kind of guaranteed figure that the author suggests.

Outside the farmhouse there is a great deal of very hard work to be done, from which much of the toil can be removed by electricity. The small family farm depends very largely on stock and stock products for its income. A very important field of application of electricity is therefore to milking machines and to the machinery associated with milking—the sterilizer, the provision of hot water, and so on. To capture the largest possible demand which agriculture can provide, principal consideration must be given to milking and all its associated equipment and to the machinery used for the preparation of food for livestock.

Barns should be equipped with electrically-driven small hammer mills, small mixing machines, and hoists for moving materials. We want the agriculture of the future to be attractive. At the moment, on most farms young men have to move on their backs sacks weighing 18 or 19 stones. I suggest that if the best that we have to offer recruits to the agricultural industry is that they shall take part in a heavy-weight lifting contest every day in the week, we shall not attract the best men.

To interest the farmer, electrical supplies must be very efficient and well installed. The lighting of buildings is not merely a question of putting up a bulb to replace a hanging lantern. You must show the farmer how to make the best use of electric lighting.

We wish to see a national scheme for the application of electricity to farms generally, with a standard form of equipment. We want a standard, cheap and efficient supply, with easy and readily available maintenance, wherever the farm may be. So far as the large-scale enterprises are concerned, they are generally in the hands of men who are thoroughly businesslike—the grain drier, the specialized market gardener who wants soil heating and soil sterilization, the fruit grower who wants cold storage, and so on, and, in the main, they can well be left to look after them-

selves; it is the 200 000 small farmers who we believe are the best potential customers of the electrical industry.

Mr. H. W. Grimmitt: The farm load has a low load factor, but an examination of the statistics for undertakings that are really rural shows that the load factor is increasing steadily each year. Most of these undertakings return a figure of a little over 40%, which is, in my opinion, good. Too much attention need, therefore, not be given to the maximum demand of individual farms. Farm loads are very diverse, and as long as the overall load factor remains stable or improves, there is no need to penalize the farmer by an onerous minimum guarantee charge, or perhaps a tariff with a high maximum demand charge.

I hope that this paper will encourage undertakings to produce better statistics so that the supply industry as a whole can publish something which is really useful and which will show, particularly to farmers, the good work that has been done.

The portion of this paper in which I am most interested is that dealing with the layout of farm machinery. It is necessary to think of farm mechanization as a complete entity, but the present installation of plant on most farms is rather an improvisation. Now that farm workers get £3 and over per week they have become valuable; consequently manual work or manhandling has to go, and the plant must be laid out to the best advantage. There is great scope, therefore, for small conveyors and hoists.

Most existing farm buildings are in a stage of decay and ought to be rebuilt. With this opportunity, which I hope will come, the layout of plant should be given the closest consideration.

Lt.-Col. Philip Johnson: I feel very optimistic not only about electrification but also about the general mechanization of farming, since recently there has been a considerable increase in the cost of agricultural labour in this country. I am convinced that the question whether an industry will be mechanized turns simply and solely on the cost of labour. More than thirty years ago, I was asked by a zemindar in Southern India whether it would pay him to abandon the old sickle and go in for a reaper. I told him that it was just a matter of figures, and on examining his current costs I came to the conclusion that it would not pay him to contemplate ricking with a reaper unless and until he was paying at least 4d. a day to his labour. As labour in Southern India in those days was 2d. a day for men and 1½d. for women, it obviously did not pay him.

A point which struck me about the paper was that the author did not refer to the possibility of cultivation by means of electricity. This is a very thorny problem. Many people have tried it and given it up; but I feel that if some electrical engineer with time and enthusiasm, and a certain amount of his own or somebody else's money, would settle down to the problem, something might be achieved even for the comparatively small farm.

In the case of large cable ploughing tackles formerly in use, one engine was located at each end of the field, and the implements were hauled backwards and forwards across the field on a cable. This tackle has now practically disappeared, its place being taken by the tractor, which operates over the land. With a tractor, from 50–60% or even more of the total power available at the engine is wasted in transmission, in deformation of the land or in the rolling resistance of the wheels in passing over soft ground. An electrical method might be devised of operating the old ploughing tackle, which died out largely because while one man drove each steam engine, four or five were needed to feed them with coal and water. A small, light and inexpensive electric tackle on these lines might be most useful for large market gardeners, who use intercultivation implements almost continuously for many months. The whole outfit could probably be so arranged as to be controlled electrically by one man seated on the implement.

Mr. F. E. Rowland: This occasion should not be allowed to pass without paying a tribute to the work of the late Mr. Borlase Matthews, through whose untiring efforts the electrical needs of agriculture were made known in the early days.

The author's work is associated with his position as Secretary of the Rural Committee of the E.R.A. Prior to the establishment of that Committee, agricultural investigation had been handicapped by an academic approach, with undue prominence to the less practical applications, such as cultivation and electroculture. Mr. Leslie has appealed to the electrical industry to show a united front in dealing with the electrification needs of agriculture, and I submit that from the technical aspect this need is being met by the E.R.A., which is producing results unsurpassed in any other country.

The improvement of load factor on farms is an important matter. By carrying out operations over a longer period with smaller power, capital cost is reduced and the load factor materially improved. The author has described the valuable work which he has done in the development of the 3-h.p. hammer mill, which takes the place of a mill requiring a motor of 10 or 15 h.p. This technique should be more widely developed for applications such as threshing, food mixing and other processes. An important issue connected with this development is the improvement of the layout of farm buildings. Undoubtedly the electrical industry can make an important contribution in this field.

In the early days of agricultural electrification there were suggestions that special motors were required, but in practice standard protected machines have proved satisfactory for farm conditions. For certain situations due to dampness or similar causes a totally-enclosed motor is required, and where there is excessive dust a cowl-cooled machine offers a satisfactory solution.

Grain-drying is an application in which interest is being displayed, and, while there are difficulties in applying electricity for the heating load, there are great advantages, from the farmer's point of view, including labour saving and an improved sample. Considerable trouble has been experienced in producing a satisfactory milling and germinating sample. These difficulties can be overcome by the close control achieved with electric heating.

It is in the dairy that electricity has made the most progress up to the present. There is need for some clarification in the classification of the performance of steam raisers, particularly because the non-technical user finds difficulty in differentiating between pressure in lb/in^2 and evaporative capacity in lb/hour. The heaviest steaming duty on a farm is sterilizing a recording milking plant, and it has been demonstrated that this can be done electrically with a negligible pressure. With fuel-firing, however, a pressure of 60 lb/in^2 is specified, this being largely due to the inability of a fuel-fired steam-raiser to deal with a fluctuating load unless it has a reserve.

The author refers to the importance of servicing electrical equipment, and it is to be hoped that as farm electrification becomes more widespread the regular servicing of equipment will be practised. In the lighting field there is undoubtedly room for a scientific approach. In view of the great susceptibility of farm animals to shock, even on very low voltages, the safety of installations, particularly in places such as cow-sheds, is of very great importance. One solution is to isolate the electrical installation from all parts with which the animals come in contact, and another is the employment of leakage trips.

Mr. J. A. Sumner: The author states that "it is indeed difficult to visualize, in the light of our present knowledge, a practicable type of electrically-driven field power unit having the versatility required in war time." In the same way it was equally difficult to visualize, only one generation ago, a practicable type of aeroplane engine which had the versatility required of it in war time,

but that has not stopped the aircraft engine being developed. I suggest that by now we ought to have visualized and put into effect an electrically-driven field unit, because the low load factor on farms, about which we complain so much, is entirely due to the fact that we have not obtained the work on the land.

I have been trying for some time to raise some enthusiasm in the industry, in the E.R.A. and at the Electricity Commission, for development work in connection with an agricultural unit to take the place of a tractor, but do not seem to have got very far. Col. Johnson has, I think, given us a very clear indication of the possibilities of this development if only we will all play our part in it and have sufficient faith.

The author refers to the uneasiness of supply undertakings who might have to connect up to a 9- to 15-kW load and, in another case, a load of about 150 kW for grain drying. I do not think that any supply undertaking should feel uneasiness in connecting up a 9- to 15-kW load; if they do, there must be something wrong with their mains system.

Grain drying and grass drying can give a very good load, the former being equal to at least 25 000 units per year for each farm which uses a combine harvester, and the load can be entirely a summer load. The electrical industry can give farmers the scientific means of grain drying which is so urgently required: but we should not, to my mind, waste our time in trying to convert the present crude form of grain drier, using coke, to electricity by putting in resistance elements and obtaining an efficiency of heating which is very little better than when coke is used. We can, and should, develop an electrical method of heating the grain that would in the first place be regenerative, and in the second place use either radio-frequency or infra-red means of heating, or one of several other scientific methods of the application of heat that could be made reasonably simple to handle.

I should like to suggest to the author and to the supply undertakings that they should consider much more carefully the possibility of undertakings making a provision of plant for co-operative electro-farming for use by the farmers. We cannot wait for the farmers to spend several thousands of pounds on electrical apparatus: we have to spend some of the money for them. We do not hesitate to spend some hundreds of thousands of pounds in providing cookers, and I do not think we should hesitate in spending a good deal of money in providing the farmers, by hire or hire-purchase, and on a co-operative basis, with much of this equipment.

Mr. E. W. Golding: It is important to realize that about 64% of the 390 000 farms in England and Wales are actually less than 50 acres in extent. A recent report of the Institution's Sub-Committee states that to-day there are some 35 000 farms connected to the electricity supply, but that most of these farms have a greater acreage than 50, which means that future development must be devoted mainly to the electrification of the small farm. In acreage, the larger farms occupy something like 83% of the total area, leaving the small farms to account for only 17%. At the same time, it is quite possible that the load which can be obtained by electrifying the small farms may be quite out of proportion to the comparatively small total area which they cover.

I agree entirely with the author as to the difficulty of obtaining reliable information on the utilization of electricity on farms. Perhaps the recent census of farm machinery may help in this respect. I think that a detailed survey of the application of electricity to various farm processes would be most helpful. Recently I spent much time in estimating the total possible consumption of electricity if all farms were electrified, and arrived at a figure of about 1 000 million units; the possible power required would be 4 500 000 kW. These totals do not cover field power, but would be at least doubled if field processes could also be electrified.

The electrification of the farm buildings is certainly the first step, but I am a little uneasy about the question of following up some of the applications mentioned by the author. While manual labour is certainly irksome, at least it is simple, and if we electrify to the very full extent suggested and have to use these somewhat complicated pieces of equipment the latter must be properly installed and properly maintained. The units of equipment are not standardized and are not the acme of simplicity to use; they need very careful supervision in installation and for some time afterwards if they are to give satisfactory service in the hands of non-technical workers on the farm.

My last point concerns putting the matter across to the farmer. I am certain that although the young farmers, in particular, are very willing to adopt electrified methods, they just do not know what can be done, and the publicity methods in the past have been hardly sufficient to enable them really to appreciate the advantages of electrification.

Mr. W. Riggs: Several papers on the application of electricity to farming have been read here and elsewhere in the past, but usually at times when the farming industry was in a state of deep depression, when the farmer had no money to spend, and the supply authorities took no interest in him. This paper comes at a very opportune moment, when farmers have the money to spend, and their minds are more receptive to bringing their equipment up to date than ever before.

I believe that there is a committee sitting at the present time which is sponsored by the Royal Agricultural Society of England and is composed of representatives of landowners, farmers and agricultural labourers; it is considering how to maintain and increase the productivity of the land and the good of the agricultural community of this country. This shows that now is a very opportune moment to consider the question of the electrification of farm machinery to the limit.

Some speakers have already said that a holding does not necessarily imply buildings, and that several holdings may be combined in one farm, but if so they should be catered for electrically, because the farm buildings have to deal with the whole produce of the acreage. I have been told by the National Farmers' Union, quoting from the Scott Report, that it is estimated that in 1938 only 25 000 to 30 000 out of the total of 366 000 holdings were connected to electricity supply mains. It seems to me that there will be a very great deal for electricity supply undertakings and electrical contractors to do in what we hope will be the very near future in the electrification of farm buildings.

Mr. Martin Harvey: We have fitted slip-ring motors up to 15 h.p. on the skids the author has shown, and they work well. The whole secret is to put the motor right at the end of the skid, where it acts as a lever.

In the Shropshire area we are fitting an electric grain-drying plant this summer. Although it will probably cost the farmer 65–70% more to run than a coke-fired plant, he is so concerned about the bad control of his coke-fired plant at the present time that he thinks the extra cost of using electricity will be well worth while. He is anxious to avoid over-dried grain, which, of course, will not germinate. By electrical methods he can save two men two hours a day at the start.

There is now a good demand for the pressure-tank-storage type of pump. It saves the building of large reservoirs and tanks at an elevation of 40 ft, but there is one point to be watched on the practical side. With drinking troughs round the fields a smaller low-pressure reservoir fed by a ball valve from the high-pressure system is required; the best method is to put a 40- or 50-gallon tank up above the milking shed for supplying water to cow sheds fitted with pressure-type drinking bowls.

The layout for cow-shed lighting shown in Fig. 14 is a practical one, and has under-floor lighting in the washing stalls which the

cows enter before they go to their ordinary milking stalls. There are six washing stalls, and glass panels of 18 in^2 are let into the floor. These panels have not yet been fitted, but are in use in Scotland. The electric boiler is not placed near the milking machines in the power room, as the sterilizing chest is "on" for an hour and constant water by steam injection in the bottle-washing troughs is required, so that it is much better to have the water as near as possible to where it is wanted. Even 20 ft of pipe increases the heat-losses.

Mr. S. A. Stevens: In Section 3.1, dealing with motors, the author says: "While the advantages of the polyphase motor are generally admitted, there is no longer the tendency to regard single-phase motors as a temporary expedient." I suggest that, for several reasons, it is undesirable to regard single-phase motors at all. First, industrial applications of motors have become standardized for 400-volt 3-phase 50-c/s systems. Cheap motors for agriculture must therefore be standardized for the same systems. Again, motors to be small and light must be three-phase, which is also necessary if starting arrangements are to be kept as simple as possible and if centrifugal switches, commutators, short-circuiting gear, etc., used on single-phase motors are to be dispensed with.

I agree that the supply companies do not want to run a three-phase distribution network round farming areas, because the majority of the load can quite easily work on single phase; but where mechanical power is required the 3-phase motor should be used. In the last few years systems for the efficient conversion of single-phase to three-phase have been developed. In particular, there is the static system on which I have been doing some work.

During the war there has been a parallel development among garage proprietors and boat builders who have turned to war production and more and more adopted mechanization. As their supply is limited to two wires entering the premises, they have had to use phase-convertor systems to run machines with their small, compact, built-in, three-phase motors, which cannot be replaced efficiently by single-phase motors. If that can be done by the garage proprietor and the boat builder, I am sure that it is the right solution for the farmer.

Mr. G. O. McLean: In Section 2.1 the author mentions the absence of statistics on the use of electricity on farms. Our experience in an area covering 15 000 square miles is that all farmers *want* a supply. The supply authorities in the rural areas could do very much more if times were normal and they had the material and the labour to do it. The author's statement that farmers who do have a supply make use of it, is supported by an analysis of some samples taken from farming areas covering 15 000 square miles from the Wash to Land's End. We analysed statistically the consumption for some 50 good farms from each of 4 areas, deducing frequency distributions and graphing them and working out the usual constants, and found that of those farms which had supplies in the farmhouse only, about 25% of the total, had modal consumptions of 2 000 to 2 500 units per annum. I suggest that this indicates the use of electricity for more than lighting and a radio set. In fact, the farmer's wife has discovered the value of electric cooking.

The second class of consumer indicated by this analysis covered those farm buildings which had motive power; in all four areas these had the same modal consumption, about 8 500 units per annum. The average was higher, but the statistical distribution was well spread out, the range being from 2 000 to 30 000. This modal figure of 8 500 per annum means at least 4 kW of power load per farm, even allowing 6 hours' continuous running for 365 days a year. There is no possibility of that running time being used, and so the load per farm must be much greater.

The author might have made a little more of Section 4.5.2, in which he deals with water supply. Mr. Knowles, the President of the National Farmers' Union, recently referred to the need for water supply and electricity for farms. In one county, about 60% of the hamlets are without piped water supply, but not one-third of that number are without electricity supply; in fact, only 19 hamlets with a population of over 250 are without a supply of electricity. No farmer need be without a supply of water under pressure, when he has a supply of electricity and a well into which to put his pump. I know that from an electrical point of view there is not much revenue from this water-pumping load—perhaps a few hundred units a year—but the farmer will appreciate its value. Has the author any figures from British practice to compare with those given at the American I.E.E. Conference last year and recorded in the *Edison Rural Electrification Bulletin*? The cost to hand-pump about 300 gallons a day is given as £53 per annum at a labour cost of 1s. an hour. The pump installation costs £20 and the electricity 15s., so that the whole cost was paid for in less than six months and there was a financial saving of over £50 a year.

Mr. G. May: Being an electrical engineer turned farmer, naturally at the outset I desired an all-electric farm, but the supply company wanted £2 000 for the main. I therefore installed a Diesel set.

The electrical industry can help us, I think, to cut out heavy work—particularly lifting. Could a portable hoist be designed: (1) for stacking sacks, up to 2¼ cwt each, four or five high; (2) with a grab for loading dung carts, and (3) for lifting bales of 1 cwt on to stacks 20 ft high?

The most popular paraffin tractor is of 15 drawbar h.p. type, but suffers from excessive wheel-spin. Would the extra weight of a battery-driven tractor overcome this difficulty, and also provide a useful night load for supply companies?

Electricity could be useful for crop-driers, particularly to eliminate coke fumes, but the price is too high. We use 3 cwt of coke per hour at 10s., which, I am told, is equivalent to about 500 kW. We therefore need a supply at ¼d. per kWh.

Mr. J. R. Moffatt: I am in charge of the Rothamsted Experimental Farm, which has been electrified for the last ten years. We have 10 motors ranging from 20 h.p. to ½ h.p., and I was surprised to hear that the author found it necessary to contradict the suggestion that farmers do not use power for farming operations. However, the Table in Section 2.1 indicates that the majority of farms have very few motors, an average of about 1½ or less. It is not, however, entirely the farmer's fault that he is under-motored. The farmer, and especially the small farmer, has considerable difficulty in keeping abreast with modern ideas, and he does not know where to turn for expert advice on electrical machinery in particular. I suggest that there should be some means by which the smaller farmer could be kept informed of modern developments.

Although the E.R.A. is an excellent clearing house for ideas, something more is wanted, such as a few centres dotted over the country where electrical machines could be put on view under working conditions. Until some such scheme is started, it seems to me that no farmer, no matter how keen he is, can ever be fully mechanized, because he will not know how a certain operation which he is doing by hand can be done by electricity.

What Mr. Leslie calls toil, I should call drudgery; there is no need for this drudgery, as I know from experience that most of it can be eliminated. It is up to the farmer to eliminate it, not only to reduce labour costs and speed up work, but to encourage young men to stay on the land and youngsters to come into farming. In no other industry would the workers stand for so much man-handling of materials as is common in agriculture.

It is stated that it is better to use one motor for each machine—that is, the unit drive principle—rather than one large motor to

drive a shaft, with several machines driven from it. We use the unit drive principle, as being more convenient from every point of view, but is it more economical?

Maintenance is a very important question for all farmers, and especially for small farmers. Once they have electrical equipment in, they should be able to make a maintenance contract with the supply authority. We did that at the outset, and had two inspections a year of all the electrical equipment, including the wiring. That has now been reduced to one a year, two being found unnecessary.

Regarding grinding, I agree that nearly every farmer wants a different degree of fineness, but a few years ago we carried out an experiment testing two degrees of fineness of grinding for feed to pigs, fine and coarse barley meal, and found no significant difference between the two. I restrict my Essex mill to three or four screens, and find this covers the requirements of all classes of stock.

On the question of the pneumatic transport of grain, it seems to me that it is possible to eliminate nearly all bagging and subsequent man-handling. The author mentions certain possibilities. The grain as it comes to a farm could be shot into a hopper and blown or sucked into overhead bins; it could then be fed by gravity into a mill on the floor beneath, and all the man-handling could be eliminated. This is very desirable, especially with sacks weighing perhaps 2¼ cwt. With driers, instead of bagging-off I see no reason why the grain from the drying plant should not go straight into large hoppers and then be sucked or blown out into tip lorries, taken straight to the millers, weighed, and tipped into their hoppers, to avoid the constant man-handling.

Mr. T. S. Pick: As well as being an engineer I am a small-holder farmer and a firm believer in small-holdings. My comments therefore are based on the small-holder, and not on the big consumer with unlimited capital.

I am convinced that there is a field for electrical development, even for the small load not connected to the main, provided that equipment is designed for the small continuously-run prime mover. The average land in this country will only produce a 10-fold yield of grain, of a type which millers do not want. Hence, I would chiefly devote my little arable to legumes, particularly beans, though I hope that the haricot will be developed by plant breeders to form the most reliable type. The haricot is a clearing crop, taking little man-power, apparently enriches rather than depletes the soil, and has a 100-fold yield. I should feed the crop whole, both grain and haulm in the form of meal, the complete plant giving me approximately a balanced ration.

Certain of the larger hammer mills would reduce the whole plant to meal, but, as the author indicates, such mills are expensive and call for a heavy demand for power. I have prepared the design of a ball mill which would take a complete bale of beans (about 70 lb) and which would be left to rotate whilst other work was carried out. Fineness of grinding does not appear to matter, provided all the seeds are cracked. The only screening would be to remove the balls. The same mill would deal with purchased grain, it would probably deal with cake, and it is in essence a mixing machine also. The whole could be manufactured and maintained by the village blacksmith, and the power consumed would be about 3 h.p. On this basis therefore it would be no use the author offering me a threshing machine, a grain drier, a hammer mill, a cake crusher, or a mixing machine.

I am sorry the author dismisses field equipment so lightly, for liquid fuel is quite a trouble on farms well away from a petrol pump. My opinion is that every farmer needs three self-propelled vehicles: a small crawler tractor, a convertible van or truck, and a car for the family. For both the latter his radius is limited to the nearest markets or school, so that electric vehicles would be very suitable. All three are never required together, and except for some dozen days in a year the power in the tractor need only be small, about 5 h.p. Moreover, I have found that with my 10-h.p. tractor I never use more than 4 gallons of petrol a day, and a large proportion of this goes in idling. It seems to me that two 100-volt, 300-Ah batteries would fill the bill, one in the car and one in either the truck or tractor, with provision to add the second battery to the tractor when heavy work up to 10 h.p. was required.

I am much interested in the author's mention of the low-load storage steam raiser. I have just completed the calculations which I was going to try out in practice of a unit which would be in effect low pressure, because I do not consider a steam accumulator suitable for unskilled labour, and the merit of such a scheme, in addition to low-loading and consequent high load factor, seemed to be in reduction of scaling on inaccessible parts with hard water.

I suggest that it is time a complete range of low-voltage equipment be placed on the market at an acceptable price, and that farmers be encouraged to use this before electricity on the farm gets a bad name.

Mr. L. Burdes (*communicated*): The recent introduction of legislation for enforcing minimum standards of clean-milk production and also definite standards of treatment for milk, such as pasteurization, is likely to accelerate the use of electricity by the farmer. Many farm buildings were erected in an age when working conditions differed very materially from those which will be accepted as normal requirements within the next decade, and it is very doubtful whether it will be possible to bring up to date buildings of that sort. This rebuilding will accelerate electrical development. Further, the farmer who is faced with having to rebuild will be tempted at the same time to qualify for the higher category of milk production. It is true that milk production is only one branch of farming, but the farmer who finds from experience that electricity gives good service in this connection will be inclined to employ it in others.

The war would also have a tremendous effect in assisting the progress of mechanization. The younger men who have been in the Forces or the factories will have spent a number of their impressionable years in close contact with machines of all types and will be anxious to apply their knowledge to farm operations.

Considering the electrical aspect, I should like to offer one comment in connection with the design of electrical equipment for farm use. Whilst ordinary industrial designs may be quite adequate for industrial applications, I am of opinion that it will be in our interests in the long run to employ some more robust designs for farm use. The average farm worker has been brought up to treat machinery and implements in a very rough manner, and I think that designs should be put forward for equipment which will stand up to similar treatment. No doubt the time will come when the younger generation will have been brought up with different views, but I think that robustness is required at this juncture. It would be quite wrong, for instance, to assume that a tractor receives the same care and attention as even a commercial lorry. The older generation have been used to implements which would lie out in the fields for months at a time, and we have to put forward equipment which will satisfy these farmers and farm workers.

[The author's reply to the above discussion will be found overleaf.]

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. C. A. Cameron Brown (*in reply*): I fully agree with Mr. Leslie that the major problem in post-war rural electrification is possibly to supply the large number of small farms of from 50 to 150 acres with electricity and suitable equipment. It is not likely that they are so dissimilar in needs and uses that simple mass-produced equipment could not be contrived. A start has already been made in this direction with the small automatic hammer-mill now available in restricted quantities and at a very reasonable price, and with the self-contained 6-kW sterilizing chest. The former can meet all the grinding requirements and the latter all the sterilizing requirements of any farm in this class, and even larger farms. What is wanted is an order, not for a dozen, but for a hundred thousand of each. Who will be the responsible body: the N.F.U. or some electrical amalgamation?

Mr. Grimmitt correctly points to a major difficulty confronting the progressive farmer, namely with regard to antiquated buildings which are still sound structurally. In similar circumstances, the industrialist generally pulls down the old buildings and builds new ones, but in farming, ownership difficulties, shortage of capital, and even sentiment, prevent the farmer doing the same. In any case, there is little collected information on what *is* the best type of farm building. If the farmer must make do with old buildings, then electricity is the medium which can most easily enable him to mechanize, in spite of architectural and structural difficulties.

Col. Johnson has apparently overlooked the reference, admittedly short, to the use of electricity for field power made in the paper, and which is fully developed in a report now issued by the E.R.A., who are, by the way, not really so lacking in appreciation of the issues involved as Mr. Sumner appears to indicate.

Mr. Sumner is also surprised at any question of difficulty in accepting 9- to 15-kW sterilizing loads. These are really additional loads, and in an intense dairying district anything approaching a 100% connection raises the unwelcome prospect of increased m.d. charges, especially as a high diversity with dairy sterilizing equipment cannot be relied on. In his reference to purchasing or hiring schemes, Mr. Sumner strikes the same note as I have already done in my reply to Mr. Leslie, and presumably he is prepared to put forward the supply authority as the responsible body to handle the bulk supply of equipment: there is much to be said for this.

Mr. Rowland draws attention to the bogy of "pressure" which has haunted the dairy bacteriologists and the dairy husbandry advisers for years, much to the detriment of dairy practice. Fortunately, however, it is now possible to say that, largely as a result of work being done by the E.R.A., evaporative capacity is now appreciated to be the significant factor; not only so, but with the regular steaming provided from an electrical set a comparatively low evaporative capacity will meet the requirements on most farm dairies.

My experience does not make me as pessimistic as Mr. Golding in rating the handling capacities of farm workers; they have shown, on the whole, neither reluctance nor inability to handle any equipment so far put at their disposal. It is reasonable, too, to expect a continual improvement in this respect.

Mr. Stevens's remarks on the static conversion of three-phase to single-phase current are made probably in ignorance of the exact range of motors generally used on farms, where the conditions are very different from those generally associated with the static convertor. Farm motors are of all sizes, and on one farm may well range from the 1-h.p. pump up to the 15-h.p. threshing motor. Nor need any of the equipment be compact or light.

Mr. McLean refers to American figures, but these are rarely of any real value and do not seem to appeal to our farmers, who, in the case of water supply, for instance, are much more impressed by the fact that it costs less to pump water electrically than to buy mains water.

I am afraid that the extra weight of Mr. May's 15 d.b.h.p. battery would certainly stop wheel-spin if weight were all that was wanted; it would probably not, however, improve the tractive efficiency.

Mr. Pick's proposed production by the local blacksmith can hardly be serious, but if he has a machine of the simplicity and effectiveness claimed he would be doing a service by describing it fully in print. I dismissed the use of electricity for field power with no "lightness" but, as with poultry farming, etc., with a respect for the space and time allotted. I must, however, ask why Mr. Pick would deny the small-holder the use of his car for the sheer pleasure of a trip to the seaside, and why he limits his travel to market and school?

There is, too, some common ground between Mr. Pick and Mr. Burdes, and others, in having had some unfortunate experience with men, and electricity, on farms. Who gives electricity a bad name on farms? I have come across no fatality, no outcry, no indignation, although I have covered a wide range of farming and farm conditions. Nor do I find that, on the whole, the equipment is not robust. I feel that electrical engineers would do well to have more confidence in the product of their industry, but at the same time they should ensure that at no point in the chain of its application is there a weak link caused by indifferent workmanship or attention.

REMOTE SWITCHING BY SUPERIMPOSED CURRENTS*

By J. L. CARR, M.Sc., Member.†

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SUMMARY

The paper briefly reviews methods for the centralized control of switching operations on distribution networks, by injection into the distribution system of currents which differ in frequency from the main supply. The superimposition of ultra-audio frequencies for limited and specific purposes, such as the protection or the remote switching of a transmission line, has not, so far, been employed to any large extent in this country, and is therefore beyond the scope of the paper.

Several devices employed to respond to injection currents are briefly described; and the probable applications of this method of control are outlined. Particulars of the development of remote signalling over the network of a large electricity supply undertaking are given, together with reasons for the final adoption of the method selected. Particulars of the components of the equipment are given, and the power required is analysed for two frequencies.

(1) INTRODUCTION

The practicability of controlling, from a central point, load devices connected to distribution systems has long been the subject of investigation. The need for such control arose primarily from the fact that, in many districts, electric street lighting was developed after networks had been laid down for other purposes. Also, with the greater areas covered, the centralized switching of street-lighting circuits by special conductors using the multiple (or parallel) system of supply frequently proved impracticable; with a series system of supply, this limitation was less acute. These conditions were met, to some extent, by the development of automatic time switches, which eventually reached a high degree of mechanical perfection. Nevertheless, the adverse conditions of installation, and the need for periodically resetting the time switches, called for regular attention and adequate repair facilities. The later development of electrically-wound switches fitted with astronomical dials tended to reduce the amount of attention required, but at increased capital cost. But these methods of control are somewhat inflexible and cannot take account of variable climatic conditions. Light-sensitive cells have been tried, but the low limits of illumination at which they were required to work, with small changes in illumination, militated against complete success.

An obvious possibility was to superimpose a voltage with a different frequency on the ordinary supply voltage, to produce a composite voltage which could be later separated into its components by means of selective devices. A suitable combination of inductance and capacitance in series and in resonance at a selected frequency, would have a low impedance for that frequency but a relatively high impedance for other frequencies; while a combination of inductance and capacitance in parallel would give a high impedance for a certain frequency and a comparatively low impedance for all other frequencies. Sensitive receivers could therefore be designed for satisfactory operation at a superimposed frequency.

About 1910, a system embodying this principle was patented by Handcock and Dykes; a second patent in which Duddell participated was obtained in 1912.[1] Work on this development was interrupted by the last war, although in 1917 an installation put in at Leatherhead met with some success. In this system, in which relays designed to respond to the selected frequency and to definite pulsations were employed, pulsations of a superimposed frequency were sent out at regular intervals. This installation, and others in 1920 at Winchester, Tilbury and Crayford, and in 1923 at Douglas, Isle of Man, were put in by Oliver and Pell.

A method of control utilizing a d.c. signal between a network and earth was described by Reeves in 1917.[2] A similar method using a spark generator to give high-frequency current and with sequence switching, was developed in this country about 1933 and met with some success. These methods have obvious limitations.

Meanwhile, investigations were proceeding in France on the application of multi-frequency signals to supply networks, with the object of providing a plurality of switching channels. In 1928 the first large installation was completed in the Paris area,[3,4,5] its primary functions being to co-ordinate the operation of a large number of double- and triple-tariff meters, and to control street lamps. By 1936 twenty-eight emission plants were installed on the principal undertakings in Paris. The same method was employed in Maidstone in 1937; and similar small installations in which the signal currents are injected in series with the feeders have since been completed in this country. Other interests have proposed to inject audio-frequency currents into supply systems in parallel with the system, and since 1938 several installations of this type have been carried out. Detailed information on these developments has not yet been published.

A somewhat different approach was adopted in Germany in 1936. Instead of superimposing a voltage on the supply system, one phase-voltage was momentarily suppressed by a high-speed circuit breaker, and the resultant voltage distortion employed to actuate remote relays.[7]

(2) METHODS OF INJECTION

The manner in which the superimposed current may be introduced or injected into a supply system will vary considerably according to the extent of the system; the area over which simultaneous signals are to be transmitted; the desired or available rating of the injection equipment; the frequencies used; and the signal strength necessary to actuate relays at various points in the distribution networks. Engineering technique and economics also play important parts in the final selection.

The variants are divided broadly into those in which the injection is made in series with some part of the system, and those in which the injection is made through a tee connection, in parallel with the system. In the former method, that part of the system into which the superimposed current is injected should not be interconnected with other parts not receiving the injection. By injecting in rotation into different sections of the system, the rating of the ripple generator can be reduced. With parallel injection, the same subdivision of the system cannot easily be achieved, and the equipment must therefore be of higher rating for the same signal strength; signals are, however, transmitted simultaneously over larger areas of supply, instead of in sequence.

The simplest application of the series method is to provide injection transformers in each feeder or group of interconnected feeders, and to connect the ripple generator in turn to the various

* Transmission Section paper.
† Manchester Corporation Electricity Department.

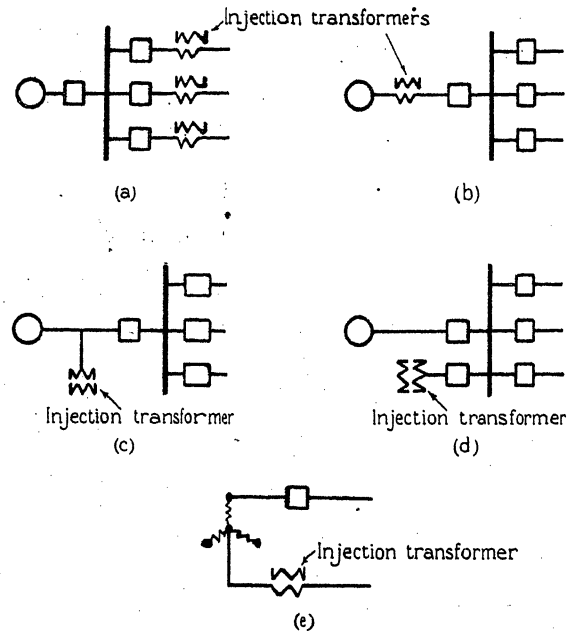


Fig. 1.—Injection arrangements.
(*a*) Series injection on feeders.
(*b*) Series injection in group feeder.
(*c*) Parallel injection in generator circuit.
(*d*) Independent parallel injections.
(*e*) Neutral series injection.

feeders (Fig. 1*a*). The Paris installation is the outstanding example of this method. A similar result may be achieved by injecting into the whole of one section at the same time (Fig. 1*b*), using an injection equipment of increased rating. With parallel injection, a single connection to the busbar would be required, as shown in Fig. 1*c*. In all these methods, three-phase ripple equipment would be employed, the superimposed current travelling through the load at the remote end, and through the generator (or supply transformer) windings at the supply end. The main differences are principally constructional; in the first example, a relatively large number of injection transformers have to be erected in the high-voltage feeder cubicles; in the second, the injection transformers have to be inserted in the group feeder, generator, or transformer circuit, according to circumstances; and in the third case the transformer for injection is independent of the other circuits. Apparatus in the first two examples must be capable of withstanding the effect of the full short-circuit power of the system for all ongoing faults. In the third case, the apparatus does not carry short-circuit current for system faults. By installing a circuit-breaker (Fig. 1*d*), the injection equipment may be isolated from the system when not actually in use, and existing connections remain undisturbed.

Parallel connection to the supply system may also be effected by capacitors, instead of transformers.

Where current is injected into a three-phase four-wire system it may conveniently take the form of single-phase current or even direct-current interposed between the star point of the supply transformer and the neutral conductor (Fig. 1*e*). With this arrangement, only those loads connected phase-to-neutral carry the superimposed current, enabling the rating of the injection equipment to be reduced. The method is, however, somewhat restricted in application.

Busbar-sectionalizing arrangements on larger high-voltage systems may make it difficult to provide approximately equal signal strengths at different parts of lower-voltage systems. For example, in the arrangement in Fig. 2, the several sections of feeder busbars are supplied from the main (generator) busbars by group feeders in which reactors are installed. Short-circuit considerations indicate that injections might, with advantage, be made on the feeder sections. The large number of feeder cir-

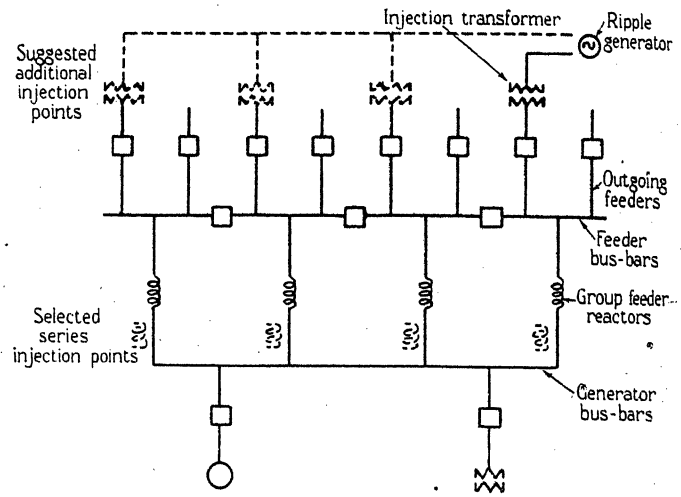


Fig. 2.—Modification of single parallel injection to multiple or series injection, to give approximately uniform signal strength on outgoing feeders.

cuits, only a few of which are shown, suggests that parallel injection is to be preferred to series injection. The interposition of reactors between the injection bars and the generators and transformers in shunt would be an added advantage in parallel injection. The selection of a single point of injection on one set of feeder busbars would, however, necessitate the transfer of the bulk of the ripple current through one reactor to the generator busbars; a loss through the generators in parallel; and the distribution through group-feeder reactors to the other feeder sections. A uniform ripple voltage on feeders could not, therefore, be obtained, the disparity depending on the reactance, ripple current and frequency employed. To obtain approximate equality of signal, two methods are available: with parallel injection, to provide an injection point on each feeder section; or, with series injection, to install injection transformers in the group-feeder circuits. The latter method was, it is believed, adopted in one installation.

(3) VOLTAGE AT POINT OF INJECTION

Most large supply undertakers operate an interconnected transmission system at 20 kV or above, with main substations transforming to a secondary high-voltage for feeding transformers for works supply and distribution networks. For the simultaneous reception of signals over the whole area, injection into the transmission system presents obvious advantages. Problems of robustness and insulation of apparatus employed at the high voltage and high short-circuit duty required would be considerable, particularly if a large number of series transformers were to be employed, while the interconnected character of the network would generally increase the difficulties of series injection. Injection at the secondary high-voltage would require several ripple generators, whose action might be synchronized by pilot cables to a central point. Insulation problems would be much easier: but, even so, the provision of large numbers of feeder-injection transformers would be a formidable task.

Injection into distribution networks would permit the use of simpler equipment, but would need a large number of generators to cover the whole area. Their relatively low first-cost would facilitate the gradual adoption of control by superimposition,

without high initial capital expenditure. On the other hand, fully-centralized operation would only be possible with a large number of pilot wires, or some other superimposed system of control.

In one method, relatively weak signals were transmitted over the high-voltage system and amplified at the medium-voltage terminals of distribution transformers by valve regenerators.

(4) FREQUENCY SELECTION

The selection of the operating frequencies must necessarily be a compromise between remoteness from the more likely system harmonics and other factors. Distributed capacitance of the cable networks, and inductance at transforming points and reactor positions, give the system a characteristic tuning curve. By adding capacitance and inductance to a tuning circuit, connected to a ripple generator to give approximate resonance, maximum use can be made of the generator rating for a selected frequency. With increasing frequency, more current is diverted through cable capacitance, and more voltage is required at points of reactance, with further increased capacitance current. Moreover, eddy-current losses in transformers increase as the square of the frequency. Generally, the larger the network, the lower is the tuning frequency and the lower the losses relatively. In the earlier installations the frequencies used were usually based on tests on the system concerned, but as more service data become available it should be possible to decide in advance on the optimum frequencies.

The power input to a ripple motor-generator at two frequencies and the signal voltage at a point in a distribution network, compared with the ripple current output for a large system, are shown in Fig. 3, the system load condition being approximately constant during the measurements.

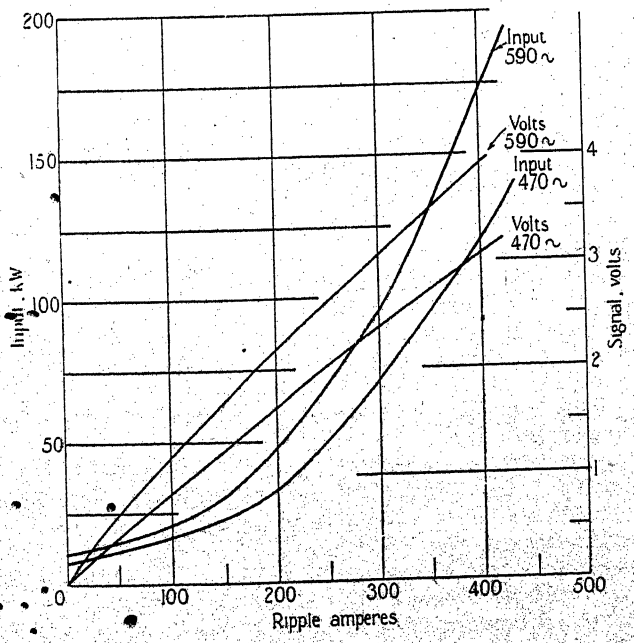


Fig. 3.—Relation between power input, ripple current and signal voltage at two frequencies; system load 178 MW.

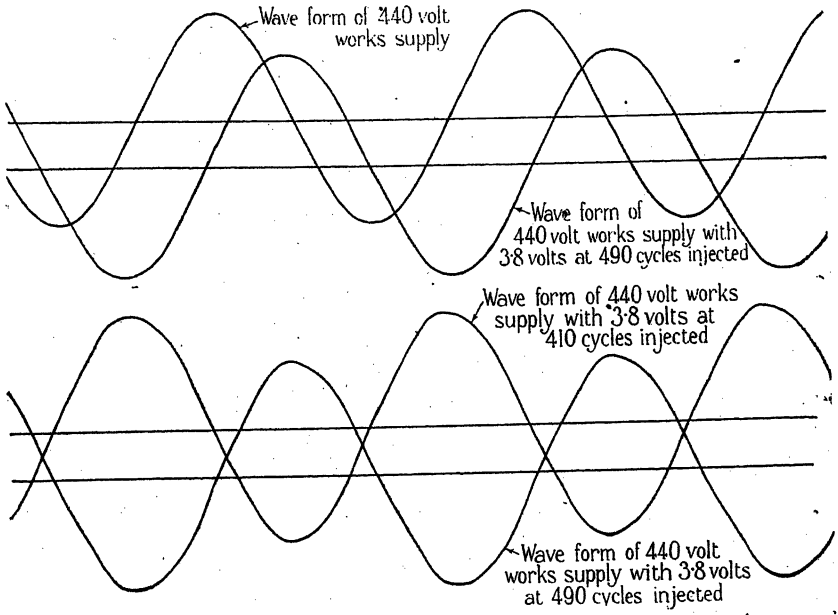


Fig. 4.—High-speed cathode-ray oscillogram for 2 superimposed frequencies during an actual operation.

(5) WAVE FORM DISTORTION

The wave form of the supply is obviously modified by the superimposition of an audio-frequency current. Diagrams purporting to show this effect, in which the approximate outline of the sine wave of the fundamental frequency forms the base of a small sine curve at the higher frequency, have been published. This effect is also revealed by the cathode-ray oscilloscope, and if the superimposed current has a frequency differing from that of a harmonic of the supply voltage, the injected sine wave appears to travel along that of the fundamental.

In practice the distortion of the wave form of the supply voltage is much less pronounced; this is shown by the traces of a high-speed cathode-ray oscillograph, reproduced in Fig. 4, for two superimposed frequencies during an actual operation. As expected, the distorting effect of a ripple of approximately 1% is very small.

(6) RECEPTION OF SIGNALS

The design of receiving apparatus is governed largely by the type of signal sent out. Where machines are employed to generate ripple frequencies, only one frequency may be transmitted at a time. For one system making use of valve oscillators it is claimed, however, that more than one signal can be sent out simultaneously over a local network.

In one system, single frequencies are emitted for a definite period, correct selection depending on careful tuning of the receiving relays and the relatively high voltage required. A separate frequency is required for each signal.

Another method uses two frequencies for each signal, the number of channels available being the product of the numbers of base and operating frequencies employed. A third method uses a limited number of frequencies, and sends out pulses of selected duration at each frequency. The number of channels provided is then the product of the number of ripple frequencies employed and the number of pulsation frequencies.

One relay used in conjunction with series injection is of the vibrating-reed pattern, the coils being tuned electrically for sharper response. The sympathetic vibration of the reed actuates, through a ratchet wheel, the opening or closing of a switch. Close accuracy of setting is claimed; the input required is about 0·15 VA.

For a system of interrupted injection, the relay is tuned electrically to respond to the ripple frequency. Two swinging armatures with natural frequencies corresponding to the pulsations of the mains are deflected by the repeated impulses, the duration of which may vary from 0·5 to 2·0 seconds. The repeated pulsation at the selected frequency causes eventual operation of the relay. A sensitivity of 0·3 volt is claimed.

A relay working on a slightly different principle is the vibrating-reed type with three reeds. Each reed responds to a certain frequency, one a base frequency which opens a switch and allows the operating portions to be energized; one for closing the circuit; and the third for opening the circuit. Near the root of each reed is a light bouncing contact, which, when at rest, short-circuits the heating coil of a thermostatic switch. The relays coils are tuned electrically, and the reeds mechanically, to the desired frequency. When the base-frequency reed vibrates, the contact bounces slightly, allowing the heating coil of the locking switch to be energized intermittently. The switch then opens, and this removes a short-circuit from the operating winding of the other reeds. Immediately afterwards, injection of the first operating frequency causes the corresponding reed to actuate a thermostatic switch, which moves to the "on" position. This operation is repeated later using the base frequency and the second operating frequency, causing the remaining reed to bring the switch to the "off" position. The base locking switch resets after a certain time. The load imposed by the bouncing contact is so small that the frequency characteristic is not appreciably disturbed during operation. The operating power required is of the order of milliwatts.

In another method, direct-current bias is introduced into the neutral of a distribution transformer. A polarized relay is closed at one polarity of the injecting battery, and opened when the battery is reversed. To obtain a number of control channels, a series of impulses is sent out, the intervals between them being determined by a synchronously-driven interrupter. At the receiving end, the first pulse starts up a synchronous clock which drives an arm over a series of contacts. If the second pulse is received when the contact arm is on the selected contact, the local relay is operated, but not otherwise. The contact arm arrives at the starting position in readiness for the next signal. A specially designed transformer type of choke is embodied to keep the induced voltage exactly equal and opposite to that of the mains; the relay thus responds to d.c. bias only. The sensitivity is claimed to be about one volt or less.

(7) PROBABLE REQUIREMENTS FOR REMOTE SWITCHING

In this country, the load most suitable for remote switching is probably that due to electric street lighting. Where individual lamps are switched, time-switch control, or remote switching by superimposed currents, can give a considerable saving. Where group switching through underground cables is adopted, reduced investment and operating charges with time switches are partly offset by increased cable costs; this possibility is therefore less favourable for economic comparison. The only data available are costs for hand-wound hand-set time switches, obtained several years ago on a system with 12 000 public electric lamps connected to street-lighting circuits, with an average of 32 lamps per switch pillar, or 8 per time switch. In the absence of more precise information, the maintenance cost of relay and contactor to perform similar duty is assumed at 2s. 6d. per annum. Comparative costs are shown in Table 1.

On a 10-year repayment basis, this margin corresponds to £4 13s. 2s. per switching position, towards the initial cost of injection equipment; or, on a 20-year basis, £7 14s. 6d.

The economic possibilities can be appraised from the number of switching positions and the capitalized cost of the central equipment. If, furthermore, the system can be extended to other switching operations, its cost will be reduced in proportion. Control of storage water-heaters is a suitable application, and the saving in maximum-demand costs, particularly with bulk supplies, may be substantial. In one small equipment this saving was claimed to have more than covered the total cost of the installation in a very short time. Probable developments in the use of low-temperature heating systems might be amenable to this form of control, with further savings in supply costs.

Table 1.—Comparison of Annual Time-Switch and Relay Costs

Item	Time switch	Relay and contactor
	s. d.	s. d.
Capital charges	13 4	11 6
Winding and setting (weekly)	6 2	—
Repairs	6 4	—
Maintenance, say	—	2 6
		14 0
Available for injection equipment	—	11 10
Total	25 10	25 10

Late shop-window lighting, and other forms of illuminated advertisement devices, are also suitable for remote control, as well as double-tariff meters and restricted-hour supplies. In some instances at least the simultaneous resetting of maximum-demand indicator mechanism might prove advantageous. Other possible applications may be envisaged.

Any system of remote switching should be capable of giving a plurality of control channels, and of expansion within these limits as and when required. Most of the probable applications now use time switches. As cheap synchronous clocks without reserve springs are not considered to give a sufficiently high standard of performance for the more important duties of street-lighting and load control, more expensive types must be adopted if winding costs are to be reduced.

To permit the capital costs of the central equipment to be met in limited applications of remote control, the cost of the relays should be reasonably low and the design and construction sufficiently good to minimize maintenance costs. It is, however, significant that the Hollywood installation was undertaken to give a better street-lighting service, and not primarily for economy.

(8) APPLICATION TO A LARGE SUPPLY SYSTEM

(8.1) Preliminary Investigations

In the latter part of 1934, small-scale operations using local transmitters were commenced employing a single frequency and sequence switches for controlling a section of public-lighting circuits. The facilities were considered inadequate for extended installation, owing to possible requirements of water-heater load control and similar uses. In 1936, the desirability of such centralized control was emphasized by the introduction of air-raid precautions.

Sections of the system were surveyed, and late in 1939 tests were carried out to determine whether emissions could be used on the transmission system to operate relays throughout the distribution networks. By that time, one major application, namely the control of street lamps, had become temporarily superfluous, and was replaced by the need for centralized A.R.P. control. More than a year later authority was received to install the equipment, and the apparatus was finally put into service in August, 1941.

(8.2) System Particulars

The area is supplied from two main generating stations, A and B, through a 33-kV underground transmission system. In station A, generation is at 6·6 kV, which is fed direct to the station's main busbars. Each main busbar section is connected to the transmission system by a 6·6/33-kV transformer. Group feeders from the generator busbars supply, through reactors and step-by-step booster transformers, feeder busbars, from which a considerable load is distributed by 6·6-kV feeders. At station B, part of the plant generates at 33 kV; the other machines are directly connected to machine transformers stepping up to 33 kV; all switching is at this voltage. Connection to the 132-kV C.E.B. system at this station is through two large transformers. The generating stations are approximately nine miles apart. In station B, the busbar sections, each with its own generator, are synchronized through reactors and a tie busbar. Adjoining sections are not normally coupled directly when the appropriate generators are on load, because of increased duty on the switchgear. At station A, a similar synchronizing busbar is planned, but has not yet been installed. Neighbouring boroughs are supplied at transmission voltage from two sections of station B.

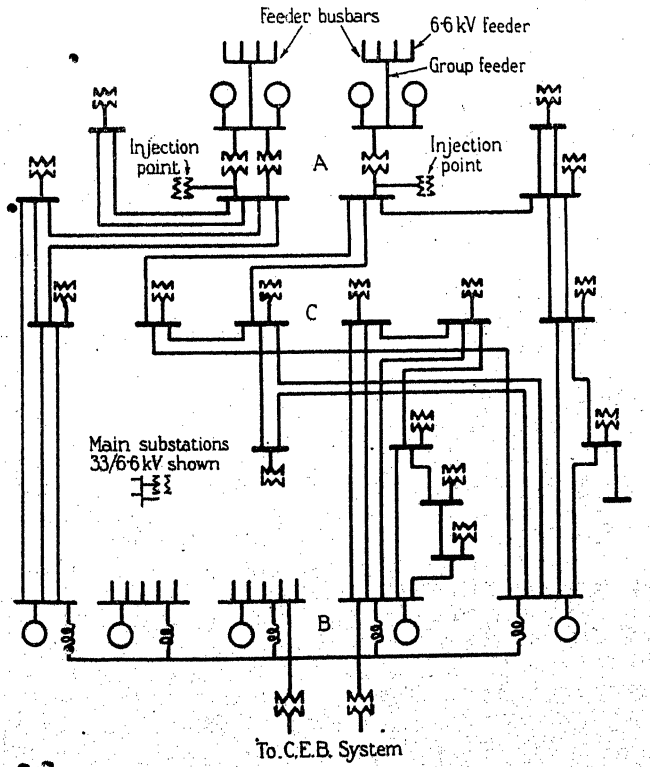


Fig. 5.—33-kV system layout with generating stations A and B about 9 miles apart.

The main transmission system (Fig. 5) comprises trunk feeders and interconnectors supplying main substations where the voltage is stepped down for high-voltage distribution at 6·6 kV. In three of the largest substations, two busbar sections are operated independently on account of high short-circuit values: these form in effect two substations on one site, and are shown as such in the diagram.

The lower-voltage side of the main transformers supplies busbars to which independent systems of 6·6-kV distribution feeders are connected. Generally, these feeders are radial, with a limited amount of interconnection on the same section where it is necessary and practicable to provide discriminative protective equipment. Each distribution feeder may supply on the average three or four distribution or works substations, where the voltage is stepped down to the standard 400/230 volts for local use. Isolated distribution networks, i.e. without medium-voltage feeders, are employed as standard at this stage of development. At substation C, a 6·6-kV generator is connected for use during peak-load and emergency periods.

Details of the system at the time the injection plant was installed are given in Table 2.

Table 2.—System Particulars

Load on associated systems at 33-kV	50 400 kW
System load	197 300 kW
Number of main substations or sections	15
Distribution substations	282
Consumers' substations	242
Cable miles: 33 kV	150
6·6 and 11 kV	420
400-volt	1 216
Number of h.v. distribution feeders from main substations	151

The alternative injection points selected are shown in Fig. 5 on the two 33-kV busbar sections at station A. Superimposed current from either of these points therefore passes through several feeders in parallel to a number of main substations, and then to the appropriate busbar section at station B. It then divides through the tie-busbar reactor system to other sections. Owing to this subdivision of current, and the relatively high current rating and low impedance of the reactors, the loss of signal strength on these other sections was not expected to be serious.

(8.3) Considerations Affecting Selection of Method

The desiderata outlined previously are capable of being more or less met by all the systems considered. Final selection is therefore governed by local considerations.

Before deciding to install superimposed-current-injection equipment, a comprehensive scheme for the installation of supervisory equipment had been worked out and would have given centralized control of a large number of distributed equipments, if the supervision had not been limited to the more important distribution points only. Injection equipments on local network would, moreover, have rendered maintenance more exacting at a time when reduction of staff was becoming serious. Also, when the decision was made, the potential uses of the equipment were restricted.

Series injection could not easily be applied to the main transmission system, and the many secondary high-voltage feeders involved precluded the use of injection transformers on each feeder. Injection into sections of the high-voltage system by employing coupling transformers in main-transformer secondary connections and group feeders only, would have simplified the problem; but a necessity for the simultaneous operation of widespread devices imposed a further limitation, and this practically ruled out the series method.

In the circumstances, a single equipment for parallel injection offered definite advantages, provided that the rating of plant required could be kept within practicable limits.

At the time, arrangements were being made to replace the transformers at station A by others, each of 40-MVA, and earthing transformers were included to make the high-voltage neutral available at this point. The projected installation of two earthing transformers on which injection windings could be erected during manufacture at relatively low cost, still further simplified the question of installation; also no additional high-voltage switchgear would be necessary. Tests on the system

showed that this layout was practicable, and it was decided to provide the necessary windings on the earthing transformers in anticipation of further developments.

The equipment finally ordered was designed for a system with a maximum load of 200 000 kVA, and to be capable of dealing with an increased load of 250 000 kVA. This is by far the largest installation of its kind ever undertaken. Several equipments for ripple control have been installed in the United States on smaller networks, the largest being about 18 000 kVA. Individual sections of the Paris system are equipped with series equipment involving automatic switching in sequence. None of the other installations made in this country is on such an extensive scale.

(8.4) Equipment Particulars

Transformers: The earthing transformers installed are rated for 18 500 kVA at 32 kV, 50 c/s, and can pass a neutral current of 1 000 amperes. The emission winding is designed for 3 000 volts, and can carry a current of 260 amperes at 540 c/s on the low-voltage side for 15 minutes every two hours. Under these conditions the copper loss is 13 kW. At 50 c/s the impedance is 14·3 ohms per phase, referred to the high-voltage side; it rises to 137 ohms per phase at 540 c/s. Either transformer may be selected for injection; as the winding constants are not exactly similar, an external fixed air-cored reactor is employed to equalize the two impedances. This allows the remainder of the injection equipment to be used on either transformer without adjustment.

Generating Equipment: The generator is an inductor-type machine designed to give 200-kVA, three-phase, at 370-590 c/s, 1 387·5–2 212·5 r.p.m. The armature coils are carried in semi-enclosed slots in the core, which is divided into two parts. A stationary field-coil is mounted between the two half-cores and surrounds the magnetic circuit of the machine; the coil is fed from a 210-V battery. The pedestals are of non-magnetic material, with the outboard pedestal insulated from the bedplate, to avoid a shunting magnetic circuit and to protect the bearings from circulating current. The driving motor is rated at 210 volts, 750 amperes (157·5 kW), and is supplied from the station battery, to ensure permanence of supply under all conditions.

A 50-c/s rejector circuit with an oil-immersed capacitor and an iron-cored choke is inserted in the output circuit to limit the amount of 50-c/s current entering the generator. A tapped air-cored reactor is used with a tapped capacitor to regulate the power factor of the ripple-generator load at the selected frequencies. The general arrangement is shown in Fig. 6.

A control board is located at the power station, and a smaller control board for certain operations only is fixed at a remote location and connected by means of private telephone conductors to the control panel. An additional remote-control point has since been connected by telephone lines to a third control position for security reasons.

(8.5) Operating Information*

The equipment as originally designed employs ten different frequencies ranging from 370 to 590 c/s in 20 c/s steps, with the omission of those corresponding to system harmonics. Four of these frequencies are used as base "gate" or unlocking frequencies, and the six others for operating control switches on apparatus. Thus, 24 operating channels are available. Apart from the initiation of the process, the operation and regulation of the variable-speed motor-alternator and injection equipment is entirely automatic and direct, without the use of gearing. All that is necessary after ensuring that the isolating switch to the injection transformer is closed, is to rotate the frequency selector switch to the appropriate position and to press the "start" button. The starting contactor closes; the motor revolves and other contactors progressively short-circuit portions of the starting resistor until the armature is connected directly across the supply.

* The MS. of the first three paragraphs in this Section was received 4th August, 1944.

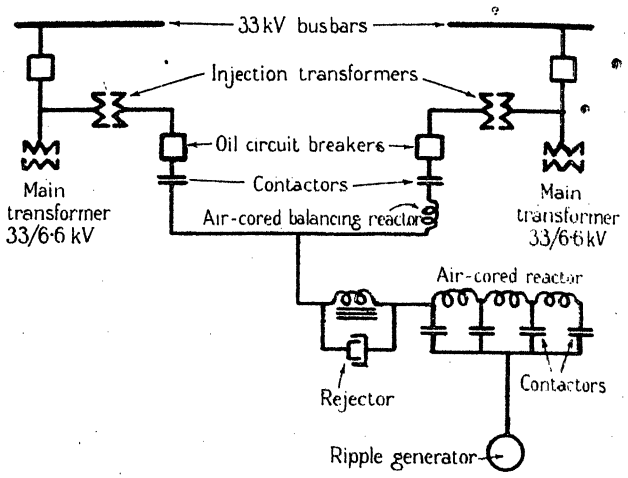


Fig. 6.—General arrangement of injection circuit.

The field of a pilot generator on an extension of the main shaft is then energized, this machine being used for frequency control. Other contactors select appropriate tappings in the tuned circuits of ripple-frequency and voltage relays; adjust motor field and generator field; and select tappings on the injection reactor and condenser.

The injection contactor is now closed and the base frequency injected for one minute, after which the speed and other conditions are altered automatically and the operating frequency sent out for a further minute. The machine then shuts down. During injection, speed is maintained constant by means of a ripple-frequency control relay having two opposed elements acting differentially and connected to the pilot generator. These elements are connected respectively to circuits tuned for frequencies slightly above and below that desired, so that the relay response is extremely sensitive. This characteristic, together with the relatively high inertia of the machine and the constancy of the battery supply, results in extremely close speed maintenance after the first few seconds. The relay causes a motor-operated rheostat in the motor field to move in the correcting direction. The output of the main machine is governed by a ripple-voltage control relay, connected to low-voltage supply mains through a band-pass filter. The filter gives substantially uniform response for slight departures from the set frequency, thus ensuring voltage stability; and it separates the mains voltage from the ripple voltage, which is then rectified and applied to the sensitive moving-coil relay.

The equipment was put into limited service until conditions became normal. As a temporary measure, it was decided to dispense with the base or locking frequency, and to operate relays on single frequency only for one particular service, thus reducing the operating time. This necessitated a modified design of relay. It was desirable to receive this broadcast signal over a wide area covering the whole district of supply of the undertaking and the districts covered by bulk-supply undertakers fed therefrom, as well as another system connected directly thereto. The total number of relays concerned was, however, not very large.

Comprehensive pre-commissioning tests with the actual installation were not practicable, and some "teething" troubles were inevitable. Also, during installation certain urgent recon-

struction had to be undertaken which disturbed the normal system arrangements. This reacted unfavourably on the initial performance of the equipment until the reason was appreciated and certain alterations were made in control connections. During this time the earlier relays suffered from frequency drift, which an examination by the manufacturers showed might be due to chemical action on the plating of the reeds. All reeds in the earlier relays were therefore changed for an improved type, after which irregularities in operation were greatly reduced.

During the early stages, fifteen instances of inadvertent operation of apparatus controlled by relays were reported. Of these, three were due to defects in individual relays; five to local voltage distortion; and the remainder to unauthorized interference with the apparatus, or to faults on the associated circuit or apparatus. As an example, voltage distortion occurred at a cinema where two rectifiers were installed, one for cinema projection and the other of 2-kW rating for battery charging. Investigation showed sufficient distortion at the service position to cause occasional operation of the ripple relay. Contrary to expectation, this proved to be due to the operation of the small rectifier connected to sub-circuit wiring of small section and considerable length. The provision of adjustable smoothing apparatus at the rectifier removed the cause of the trouble.

The reliability of the apparatus is shown by the particulars of operations over more than two years given in Table 3. The

Table 3.—Operating Performance of Relays and Controlled Apparatus

Period	Number of operations	Faulty relays	Faulty apparatus
		%	%
1941, Aug.-Dec.	13	1·38	1·15
1942, 6 months	3	0·17	0·67
1942, 6 months	6	0·37	1·83
1943, 6 months	3	0·67	4·00
1943, 6 months	5	0·10	2·40

heading "Faulty apparatus" includes blown fusible cut-outs on the supply to the controlled apparatus. Six-monthly periods have been chosen for convenience. The differences in the performances of relays and apparatus respectively are striking, and show the high degree of reliability of the relays.

(8.6) Ripple Power Required

The power input required for the ripple generator to provide a given signal strength at distribution networks may be derived from Fig. 3 for the frequencies employed. Since each relay requires only a few milliwatts of ripple energy for response, many thousands of relays may be connected without materially altering the power required at the central station. The efficiency of utilization of the signal is extremely small, judged by ordinary standards. The signal voltage determines the power required at a given frequency, other things being equal. The advantage of sensitive relays is therefore very great: but low signal voltages can only be employed without inadvertent operation, if the relay design and the method of actuation have been carefully thought out.

All consuming devices, generators and transformers connected to the system absorb current under the influence of the ripple voltage, and current will also pass through cable capacitance. Losses occur throughout the system, at transforming points, in the ripple generator and in associated equipment.

So many variables are involved that no close analysis without considerable experimental data is practicable. It is, however, estimated that at 500 c/s the current passing into the cable capacitance of the system under consideration is of the same order as, but in approximate quadrature with, that passing into the system load during day-load periods.

An extensive experimental investigation at several frequencies has not been possible up to the present. But Table 4 has been

Table 4.—Separation of Loss at 250 Amperes Injection for Two Frequencies

System Load Approximately 160 MW

Item	At 410 c/s	At 590 c/s
No-load loss in generator .. .. kW	8	11
Loss in generator and injection equipment kW	18	25
Loss in injection transformer .. .. kW	5	10
Loss in system and connected devices .. kW	12	18
Total .. .. kW	43	64
Signal voltage V	1·7	2·4

prepared from the available data, and shows how the power required is expended when a current of 250 amperes is supplied from the ripple generator.

It will be noticed that, owing to the relatively high rating of the high-voltage windings, the transformer loss, though appreciable, is very much less than if it had been designed for values of the injection current alone. This loss may be largely eliminated by employing capacitive coupling instead of inductive coupling. In another area, it is understood that the power required for satisfactory network signals was much reduced by replacing the transformer by condenser coupling.

The proportion of the power input absorbed by the system is lower than anticipated; this item must be expected to vary with the system load, and isolated readings indicate that this is so.

(9) CONCLUSION

Considerably more detailed information of these control methods should be made available when the war ends. The details in the paper provide a better understanding of the requirements, and encourage confidence in the future application of this method of control. No trouble has been experienced with the generating and control equipments, and the installation is regarded as a sound engineering job. Apart from slight initial trouble with relays, their performance has been highly satisfactory. Some difficulty in reception was experienced on one adjoining system, due principally to the reactive devices employed; at one location where a large power-factor-correction capacitor was installed, the signal strength was found to be very low. These isolated experiences emphasize the need for a careful survey of the optimum injection values.

Acknowledgment is made to Mr. R. M. A. Smith of the Metropolitan-Vickers Electrical Co. Ltd. for certain information and assistance; and to Mr. H. C. Lamb, Chief Engineer and Manager of the Manchester Corporation Electricity Department, for permission to obtain data and publish particulars of the installation.

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DISCUSSION BEFORE THE TRANSMISSION SECTION, 10TH MAY, 1944

Mr. H. Nimmo: This is the first paper before The Institution since 1939 to deal with remote control by superimposed currents, and as it deals with a relatively new technique it is very welcome. Manchester Corporation Electricity Department have experimented with carrier-current systems for some years and have now developed what is perhaps the largest system of centralized control by superimposed currents in the world. The author has given some details of the various carrier-current systems in use, but his paper provides only scanty information on the Manchester system. A great deal more information on this subject is desirable at this time of transition from the experimental to the practical stage.

The author refers to the French system which we know here as the Actadis, or "Action-at-a-Distance" system. The fundamental difference between the Manchester equipment and the Actadis is that in the former parallel injection is used, whereas the French use series injection. There may be a good deal of discussion as to which is to be preferred, particularly from the point of view of interference with other systems.

The French are a practical people, and some years ago the Cie. des Compteurs, one of the largest meter-manufacturing concerns in Europe, purchased the Marseilles Electricity Supply undertaking for the express purpose of experimenting with and perfecting their carrier-current system. When they had successfully completed their investigations, they sold the undertaking back to the original owners.

The Paris electricity supply companies then adopted the system (1) for operating at specified times each day the triple-rate meters, (2) for street lighting, and (3) for some other purposes. If the Manchester equipment proves to be as reliable as its Paris counterpart a great advance will have been made.

In view of the rapid development of such systems just prior to the war, the Electricity Commissioners considered the possibility of standardizing ripple-control systems and frequencies, but owing to the large amount of experimental equipment then in use standardization was considered to be somewhat premature. What the Commissioners really wanted was to find a means whereby a carrier-current system in one network did not spill over into adjacent networks and cause mal-operation of the relays in a neighbouring system.

The British Standards Institution co-operated in this matter, and several conferences with the interested parties were held which resulted in a draft clause for inclusion in the Commissioners' Safety Regulations being agreed upon. This clause has not yet been put into the Regulations and may not be known to many people. It reads as follows:

> "An undertaker shall not install a new or operate an existing ripple-control installation unless he is satisfied that the method of signal injection and layout of the undertaker's own network and that of adjacent networks preclude any possibility of the ripple transmission creating in any such adjacent network (even if the latter is fed from the busbars of the same undertaking) a ripple signal which could
> (*a*) operate or interfere with any receiving relays which might be installed in the neighbouring network, such relays being presumed for this purpose to be of identical type and tuning to those which it is proposed to install; and
> (*b*) operate or interfere with any receiving relays existing in the adjacent network at the time of the placing of the contract for the ripple equipment."

These are exacting requirements, and it would be good if the author could assure us that the Manchester ripple current will not affect the relays of some neighbouring undertaking and cause their mal-operation.

He has given some useful data on operating performance, and if the present record can be maintained there ought to be a good deal of further development of carrier-current control systems. Apart from its use for central street-lighting control, it may be very useful for load levelling purposes by controlling off-peak loads.

Mr. J. R. Beard: As a member of the Students' Brains Trust, I was interested in one of the questions which has considerable bearing on the subject of this paper. It was: Will it be necessary or advisable to set up a body for the allocation of injection frequencies? As the author has given so much study to the characteristics of the various systems, it would be most valuable to have his views on this point and on the general point of whether there are any other features on which it is desirable that standards should be laid down at an early stage. Admittedly there is a risk of premature standardization cramping development, but on the other hand a certain amount of judicious standardization in the early stages might save much trouble later. If the author feels that there is a case for considering some degree of standardization at the present time, The Institution could readily bring the matter to the notice of the British Standards Institution.

Mr. T. W. Ross: There are three outstanding points to be considered in the application of ripple control to power networks: (*a*) The limitations imposed by the network, its switching and transforming arrangements, together with any current-limiting reactances which may be included. (*b*) The drain of signal current into adjoining networks, including the Grid. (*c*) The introduction of sufficient signal current to give an adequate signal voltage at all points on the l.v. networks at which signalling is desired.

The limitations imposed by a normal distribution network are chiefly current-limiting reactors and power-factor-correcting static condensers, although in certain circumstances transformer feeders may be troublesome. The ripple current will distribute itself throughout the power network in inverse proportion to the impedance of the various parallel paths, and as the frequency is, of course, higher than the power frequency, it is obvious that current-limiting reactors will increase the impedance of those parts of the network with which they are in series.

Power-factor-correcting static condensers, being in parallel with the network, present a low-impedance path to the signal current and thus reduce its effectiveness. It is fortunate that such condensers are not usually employed to an appreciable extent on l.v. distribution networks, and that their effect is only pronounced where they have a kVA rating of, say, more than 25% of the step-down power transformer.

The drain of signal current into adjoining networks is again inversely proportional to the impedance of the connecting link. In most cases this impedance is considerable and the loss of the signal current is not prohibitive. Mr. Nimmo mentioned the possibility of this spill-over interfering with ripple relays on adjoining networks, and read a draft clause which may be inserted in the Commissioners' Regulations to govern the application of ripple control to power networks. The only practical way of complying with such a clause would be to signal over only a small part of the network at a time and so reduce the signal

current and consequently the signal voltage at the station bus-bars. The spill-over current would thus be reduced, but the advantages of centralized control would be lost and, moreover, it would be quite impracticable, if not impossible, to use series injection on a large number of the networks in this country.

If full use is to be made of the advantages of ripple control, the solution of this problem does not lie in limiting the spill-over, but in using some form of code with the ripple relays on the various networks responding to different codes. Several such systems have already been developed, and in general they offer other advantages besides that of preventing interference between networks.

Adequate signal strength is merely a matter of injecting sufficient signal current at the point of injection, but the maximum permissible is largely a matter of economics and practical engineering considerations. The sensitivity of the relays will determine the magnitude of the signal current, and the more sensitive the relays the smaller need be the injected signal current. A reasonable sensitivity for ripple relays seems to be of the order of 0·5% of the distribution voltage, providing that they are designed so as not to respond to frequencies which differ by more than 0·5% from the signal frequency.

Mr. E. E. Jolly: I am surprised that the author has made so little reference to the d.c. bias system of control. This system is, of course, applicable only to a.c. systems, but, in the light of post-war standardization and the ultimate universal application of alternating current, I believe that every consideration should be given to the d.c. bias system, in view of its low annual maintenance costs and its simplicity of design.

I have had considerable experience of various methods of public-lighting control from the early days of manual operation, and of the many difficulties experienced with these schemes and the high costs involved. In 1937 I reviewed the question of remote switching, with a view to getting better service and reducing operating and maintenance costs. As a result, in 1938 my authority decided to install the d.c. bias system in one section of the supply area. This proved to be so efficient and satisfactory in operation that it was decided to install the system throughout the whole of the supply area. Unfortunately the war intervened while this work was being carried out, but of the 1 300 public-lighting columns 950 were converted to d.c. bias control. About 500 relays were installed (some of the signal-receiving relays controlling more than one public-lighting column). In addition, multi-service units were installed on a small number of installations for off-peak load-control purposes, the largest single installation to be controlled in this manner being 160 kW. This system would be very suitable in any future development of the supply undertaking for controlling off-peak loads, quite apart from its use for street-lighting control.

In the early days of the war, signal-receiving units were also installed in the homes of the undertaking's repair parties, and signals were sent out whenever the men were required to report for duty following damage by enemy action. This was highly successful until severe raiding took place, when the men took cover in public air-raid shelters which at the time had not been provided with a supply.

The approximate number of signals sent out per annum on public-lighting control was 800, and for off-peak load-control purposes 60. No difficulties or failures have been recorded for any of the relays installed on the public-lighting system. Minor mechanical difficulties were experienced with the early design of substation panel, but these have now been completely rectified. The maintenance of the various items of equipment has not included any attention to the master controller, which has been operating continuously for 5 years. The substation panels have to be inspected about once every three months, although the batteries require topping up about once a month. I estimate that the approximate maintenance cost in respect of the substation panels is about £2 10s. per panel per annum. The batteries require re-plating every 4 or 5 years, but I think that this charge can be reduced by using nickel-cadmium batteries having suitable characteristics.

Mr. E. M. S. McWhirter: It seems that the ripple-control systems described require a very sensitive relay to allow the rating of the injection equipment to be kept within reasonable and practicable limits. The author presumably defines those limits as the difference in cost between wound time switches and his sensitive relays.

While he claims that there may be maintenance advantages with a centralized equipment, many advantages are offered by a local distribution of direct current from each low-voltage substation, and by controlling these substations, at any rate in a metropolitan area, by telephone circuits. These advantages might usefully be enumerated.

First, the problem of standardizing ripple frequencies which may become necessary would be solved by standardizing on a frequency of zero and using direct current. To deal with a potential breakdown of the centralized equipment, at least part of it must presumably be duplicated. A d.c. system injecting at each local substation would avoid complete failure over a whole area, faults being limited to a substation area. Secondly, on the question of exporting ripple frequency, as the power transformers themselves form a complete barrier, no signals will be exported when using direct current.

The third point is the question of sectionalizing this form of control for the future to avoid large load disturbances due to the control. Could the author indicate whether any equipment will be available for sectionalizing the network so that signals could be operative section by section. Presumably such equipment, if placed at strategic points in the network, would have to be remote controlled. Here again the advantages of local d.c. injection controlled over telephone pilots which are readily sectionalized are obvious.

Fourthly, the question of high-voltage interactions does not enter with d.c. methods of injection at the low-voltage substations. The author mentions that some urgent reconstruction which had to be carried out, adversely affected the operation of his control system, and that when the trouble was located it had to be put right by switching within the system and using some other arrangement. It seems to me that any control system which requires a continual watch on the high-voltage effect has very serious limitations, particularly when there are other systems available without these limitations.

Finally, on the question of cost I have collected a few figures relating to some 28 installations of d.c. bias signalling systems which operate a total of 8 500 control units for street-lighting purposes from 166 substations. The systems were used for other purposes—A.R.P., etc.—after the outbreak of war, but these units are not included in the above figures, nor do my cost figures include them. The capital charges per relay controlling up to 2 kW of load on its own contacts work out at 5s.; the capital charges for the central control and substation equipment, at 3s. 9d.; and the rental of Post Office pilot lines from the central control to substations on the basis of 1 mile per substation, at 3s. 1d., making a total of 11s. 10d. A maintenance charge of just under 1s. must be added. All these charges are per annum per relay-receiving point, and the substation charges include the complete replacement of the battery within the period of ten years. As with other systems, the cost can be considerably reduced per receiving point as the scope of the system is increased.

Mr. R. M. A. Smith: Since 1936 many scores of networks have

been examined and analysed with a view to installing ripple control, and in only one has it been found impossible to apply any known system. Of the installations actually carried out, only one system has had to be of the series-injection type mentioned in the paper, and in that case it was both necessary and feasible. All the other installations use parallel injection. In those systems put in earlier than that described in the paper, injection was made on to 400-volt busbars of a works transformer or similar suitable power transformer, while the later ones, owing to developments in high-voltage condenser technique, have been of a more efficient kind, where the injection of ripple power has been made directly into the h.v. busbars or circuits of the supply undertaking concerned. The installation described is intermediate between the two, as it is a transformer-injection scheme but has also a 3 000-volt injection circuit with 3 000-volt condensers. At the time it was installed it was considered a very efficient injection circuit, but the use of high-voltage direct-connected condensers has enabled far more efficient injection circuits to be devised. At present, some installations are working with direct-connected condensers up to 33 kV, and on networks, apart from that described in the paper, of up to 50 000 kW m.d. Some of these networks cover very wide areas. The largest one covers about 800 square miles, and simultaneous ripple signals are given over the whole network. It is difficult to see how any localized system of control, such as the d.c. bias system, even if centralized by means of pilot wires, could either economically or efficiently be employed over such wide areas.

On the economic aspect of centralized control, the paper shows that an outlay of £6 000 to £10 000, if necessary, is justified in providing centralized control equipment on a large network, even if only one set of switching operations is concerned, i.e. for street lighting. If any further justification were needed for the greater capital cost, we have only to consider its use for the centralized control of off-peak loads, thus filling in the valleys of the load curves with revenue-producing units.

In the German system mentioned, where one phase-voltage was momentarily suppressed by a high-speed circuit-breaker and the resultant voltage distortion employed to actuate remote relays, were the relays three-phase, and were any precautions taken to prevent mal-operation due to system faults, which would appear to give similar effects to the suppression of one phase-voltage?

Mr. W. Saville: There must be a limit to the degree of centralization in ripple control systems. Taken to the extreme, obviously the C.E.B. would be the controlling body and would therefore send out all street lighting signals, etc., for the whole of the country. This, of course, is impossible.

Centralization must stop at the supply authority and not at the generating authority. Supply authorities buy electricity for resale and they want to control it in any way they please, hence the operation of the ripple control system must be vested in them.

It cannot be guaranteed that the injection of audio frequencies into the mains in one area would not affect other areas, and any ripple control system must take cognizance of this fact and be immune from its effect.

Immunity can be obtained by the use of "gate" signals, that is, each operating signal is prefaced by a pre-setting signal individual to each control system in the area.

The possible applications of ripple control in the future will demand a multiplicity of signals, and any system which is limited to 10 or 20 signals is, to my mind, inadequate. Probably 50 to 100 signals will be needed.

Mr. E. Hallowell: I should like to underline the necessity of having proper discrimination and interference-free operation. In Section 7 the author states: "Any system of remote switching should be capable of giving a plurality of control channels, and of expansion within these limits, as and when required." This is obviously a desirable state of affairs, but it is difficult to understand how it can be achieved with a control system employing simple frequency discrimination within the limited frequency band of 370 to 590 c/s. Is there any significance in the oscillograms showing the conditions for two superimposed frequencies of 410 and 490 c/s? And is this the minimum separation consistent with interference-free working and having regard to the intervening ninth harmonic of the power frequency? If so, how will it be possible to accommodate eventually the various facilities mentioned in Sections 8.1 and 8.2. I believe that, in all, these facilities will call for some 40 channels. Will the author indicate the minimum frequency separation for interference-free working and the margin to be allowed for the harmonic belts? In any event it would appear that the author's limited operating experience with wide frequency separation and single service working is no criterion of the trials and tribulations ahead with much finer tuning and a greater number of channels.

The problem cannot be solved by the simple expedient of increasing the frequency band-width, since any supply system has some optimum frequency and any substantial divergence from this value is responsible for a great increase in the loading of injection equipment for a given signal strength.

The undertaking with which I am associated was one of the first to adopt parallel injection into an 11-kV system, and in view of the experience gained at that time I was led to the conclusion that a satisfactory multi-facility service could be achieved only by superimposing low-frequency beats on the carrier frequency. The advantages of such a system over one employing simple frequency selection are twofold: (*a*) the number of carrier frequencies may be reduced to a minimum, and (*b*) interference due to parasitic frequencies is completely eliminated. The beat frequency would be immune from the kind of interference experienced by the author and referred to in Section 8.5, and also from the less-known "tooth ripple" interference generated by induction motors. By using only one or two frequencies it would also be a relatively simple matter to arrange a stopping circuit in the main reactors to prevent feedback into the Grid.

I appreciate that the advantages of d.c. bias control are particularly applicable to small networks, but for a large system having a multiple voltage-distribution system the cost of renting Post Office lines over long distances would prove to be prohibitive.

Looking to the future, it is probable that many facilities at present not visualized will be demanded; for example, there is great scope in the direction of substation control. My view is that any standardization of ripple control should call for at least 60 operating channels, so as to legislate for these future developments.

Mr. J. F. Mackenzie: In the injection methods discussed, the grounds for estimating which is the best are not very clear. There are two main considerations: (*a*) does the method interfere with the normal running of a system, and (*b*) is it economic? Series injection does impose restrictions on normal switching. Again, is the limitation of ripple energy the primary factor in deciding which is the most economic system? From the examples discussed, it appears to be much more economical to be prodigal in the use of ripple energy than to spend money on its restriction. I am convinced that there is no "best" method, and that each network must be considered on its own merits. A control system able to apply any method of injection has obvious advantages.

Regarding frequency selection, each network has a specific frequency at which propagation is most efficient, but as a range of frequencies is employed it would appear that advantage cannot be taken of this. A system utilizing a single frequency would have obvious advantages.

The importance of harmonics has not been emphasized sufficiently in regard to their influence on the operational and economic aspects. Two methods of dealing with them are available. One is to design the relay with characteristics different from the network harmonics, and the other is to raise the sensitivity of the relay above the maximum distortion which appears on the network. Raising the operating voltage materially affects the economics of the system, because considerably more power is required.

If the proposed new clause in the Commissioners' Regulations implies that the ripple signal must not operate or interfere with any other system, and that "any" is then qualified by the words "of a similar kind," any new system must be of the same type as that on the neighbouring network.

Mr. P. Schiller: The author heads his paper "Remote Switching by Superimposed Currents," thus adding to the variety of synonymous terms already in use, such as Superimposed Control, Ripple Control, Centralized Control, Centralized Remote Control, Impulse Control, Carrier-Current Control, and so on. In view of the growing importance of the subject thus described, I would suggest that an appropriate term be standardized by the B.S.I., even before the latter tackles the more formidable problem mentioned in the discussion. Incidentally, I doubt whether the time is at all ripe to attempt technical standardization, considering the variety of systems still competing, and the progress still being made in the choice and combination of ripple frequencies.

The system of centralized control adopted by the author is attractive, because of the minute power requirements of the relays and the consequent simplification in injection plant. Although the detrimental effect of power-factor-correction equipment in the distribution system is minimized, these ripple-absorbing condensers still present a problem; and since their use is increasing it would be interesting to have the author's comments.

The author does not state the actual number of relays installed; it appears that there are not very many. However, with an average of 0·3 % failures during 1943, the operating reliability does not yet appear sufficient for large-scale application in domestic premises. Suppose that at some future date one third of Manchester's present 150 000 domestic consumers were to be equipped with control relays, then a rate of 0·3% would mean that on an average there would be with each operation 150 failures. A much lower rate of failures has been claimed for the system used in Paris, but it may be expected that the apparatus installed in Manchester is capable of further improvement.

In conclusion, I would ask the author to give a rough idea of the first cost and maintenance cost per consumer, based on an installation controlling, say, 10 000 consumers.

Dr. E. Billig: The scheme as described by the author is not one that would recommend itself in normal circumstances. It suffers fundamentally from the relatively high reactance of the coupling transformer to the transmission of the high-frequency signals and the subsequent necessity of designing the high-frequency generator equipment for a rating corresponding to many times the received signal strength. In principle the h.f. generator is connected in series with the impedance of the coupling transformer (given as 136 ohms in Section 8.4) and the equivalent load impedance (about 7.5 ohms per phase referred to 540 c/s and 18·5 kV phase-to-neutral). Hence most of the generator input is required to overcome the leakage reactance of the coupling transformer. On the other hand, it would not be safe to reduce this reactance any further. Even as it stands, a short-circuit at the low-voltage terminals would draw 53 times the rated current through the low-voltage winding, which must be built very strongly to withstand the corresponding electromagnetic forces. The injection winding in the transformer is rated for 1 350 kVA, about a hundred times the useful signal output. Except in the rather exceptional circumstances described in the paper, where an earthing transformer is required for purposes other than remote switching, capacitive coupling and the use of higher frequencies would probably be a more likely solution.

In Fig. 3 it would be useful to add the kVA input to the generator. It is not stated at what point of the system the signal voltage—apparently referred to the phase-to-neutral voltage of the l.v. system, 231 volts—has been measured.

Mr. A. J. Gibbons: The paper has demonstrated most admirably, and with most interesting operating data, that ripple control of switching for selected functions is a genuine technical and commercial success on a large network. Also, the trend of the discussion has shown that in the future, when we are free from a large number of war-time restrictions on labour and priority of materials, there will be tremendous developments all over the country with regard to ripple control.

I am somewhat concerned about this possibility of spill-over of signals from one network to another; those companies whom we supply are very interested, I am sure, in the possibilities of ripple control, and it is quite possible that after the war they will adopt it. Unless there is some measure of control, complaints will be inevitable. The selection of frequencies and the coding of impulses must be handled by some appropriate central authority. It may be that with a given technical system spill-over is unavoidable, in which case steps must be taken to ensure that one system does not affect the installations of adjoining authorities.

Mr. S. A. Daines (*communicated*): For some time I have been associated with a centralized system of control for remote switching by superimposed currents, using the third method in Section 6 of the paper. My experience confirms the author's assumption in Table 1 that the maintenance cost per relay and contactor is about 2s. 6d. or 3s. per annum.

I am intrigued by his mention of simultaneously resetting maximum-demand indicating mechanisms by this method, but fail to see the purpose unless it were applied to all m.d. meters which an undertaking has on circuit, as well as its C.E.B. metering. This full application would of course kill the argument often put forward that the m.d. period of one consumer is different from that of another, and different again from that of the undertaking. The application would in fact enable m.d. charges to be made more truly representative than at present.

As to the reliability of the apparatus, I have examined some of my records and, for the convenience of comparison, Table A

Table A

Periods of 6 months in	Number of operations	Faulty relays	Faulty apparatus
		%	%
1942	8	0·94	2·82
1942	22	0·32	0·32
1943	16	0·41	0·41
1943	26	0·48	Nil

gives a summary similar to that given in Table 3. I should like the author to confirm how he arrived at his percentages, as there appears to be more than one method of arriving at a conclusion.

The simple formula I used, on the assumption that the author's is the same, is: (number of faulty relays × 100)/(total number of relays × number of operations) = percentage of faulty relays on a six-monthly basis. It is suggested that, instead of the column headed "Number of Operations," one showing "Total Number of Relays × Number of Operations" would have been more enlightening.

Table A refers to one particular section only of the total number of relays on circuit, as with present staff shortage it has not been possible to keep an elaborate "life and maintenance" record for every relay. The results confirm, however, that although my system differs from the author's, the degree of reliability is high and, in my opinion, is a good pointer to prospective users of such control systems in general.

A similar trouble of low signal strength resulting from large power-factor-correction condensers has been experienced, but an alternative supply circuit nearby allowed the problem to be easily by-passed. I should be interested in the author's method of solving this problem.

Mr. W. Szwander (*communicated*): The paper may create, perhaps unintentionally, the impression that the parallel ripple injection is always preferable to the series injection, whereas both theoretical and economic considerations, e.g. as surveyed in reference (5) of the paper, as well as practical experience e.g. with the most extensive application in the world of the ripple principle in Paris, seem rather to confirm the advantages of series injection. The interconnections of the 33-kV system in Fig. 5 precluded series injection being applied to it, and a choice had to be made between parallel injection of the 33-kV system and series injection of the 6·6-kV feeders in all individual 33/6·6-kV substations. Circumstances were here unusually favourable for parallel injection, namely absence of direct connection to the Grid or any other system, from the busbars of generating station A, the possibility of accommodating the initial windings for the ripple transmission on transformers of so large a capacity as 18 500 kVA, probably comparatively large capacities of transformers in distribution substations, etc. Each case must always be considered on its own merits, but I believe that in most cases it will prove easier and more economical to install the series-injection equipment, particularly when adding it to existing systems. The apparent disadvantages of non-simultaneous operation, when injecting individually in a number of substations, is of no practical importance: it is easy to arrange for simultaneous starting of the automatic operation of the injecting equipment in all substations, e.g. by means of an impulse sent from a central control room, and even with sequential injection to several feeder-groups, the whole process can be concluded in a matter of 1–2 minutes. This is quite satisfactory for street-lighting or tariff-control. In the system described by the author, the capacity of the h.f. generator used for parallel injection appears to me to be amazingly small, and I would not be surprised if, with time, it proves to be insufficient, not only with an increase of the system-load and of the cable mileage, which is obvious, but also with an increase of the generating plant capacity in A, which would lower the impedance shunting the h.f. generator.

Static condensers used for power-factor improvement represent paths of very low impedance to the h.f. currents, and therefore they may cause the voltage necessary for the operation of the ripple relays to drop below the required minimum. To prevent this, it is necessary to shunt the condensers with small inductive reactances, tuned to resonance with the condensers at a frequency approximately equal to the ripple frequency. This, incidentally, may be one more argument against the excessive favouring of power-factor improvement in city areas where ripple control is most likely to be adopted, and where the natural growth of the system capacitance due to the considerable length of h.v. cables is already causing stability troubles at low loads.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. J. L. Carr (*in reply*): The measures taken for the development of the Actadis system, mentioned by Mr. Nimmo, could not easily be taken in this country, so that undertakers have had to rely on small-scale experiments. It was thought therefore that the information gained from a large installation would assist in a better understanding of the problems involved.

I agree with Mr. Schiller on the desirability of standard terms. "Carrier wave" (B.S. 204, No. 4126) is inapplicable; the term "modulation" is employed exclusively in radio work; "remote control" (B.S. 205, No. 3827) refers to individual mechanical means or electrical connections from a remote-control board; and "centralized control" of switching may be exercised by word of mouth. The title of the paper was chosen accordingly. The term "telecontrol" (B.S. 205, No. 1802) seems to be appropriate, although little used; the term "ripple" would rule out the d.c. bias system.

The proposed regulation read by Mr. Nimmo would, at this stage, prove very restrictive. As Mr. McWhirter states, the only injection which is not transformable to other voltages is that by direct current. Wave traps, as suggested by Mr. Hallowell, would prevent feedback, but their installation at the higher voltages would reduce operating safety. Messrs. Ross and Saville deal with certain aspects of the problem. Ripples injected into one section of a system are transferred to other stages. With series injection the voltage at the busbars is governed by the current required for operating in one section and by the impedance of the remainder of the system. The effect on neighbouring sections may therefore pass unnoticed. In certain circumstances, however, more sensitive relays on a bulk-supply circuit fed from the same busbars may be affected. In this connection, there is some evidence to indicate that ripple voltages may be actually increased at some points, presumably by local resonance.

Investigations as to the extent of propagation of ripples should be undertaken. Messrs. Beard and Gibbons suggest an allocation of injection frequencies. My present opinion is that neighbouring undertakers should each be allotted a frequency band, located about the characteristic tuning frequency; and that either a "gate" frequency should be employed or if a single frequency is used it should be sent out in timed pulsations. With series injection, limitation of the frequency band and allocation of frequencies would probably be effective.

As indicated in the paper, local considerations may determine which method is the most suitable in a selected location. Mr. Szwander claims that simultaneous injection is of little practical importance, but in some cases it has been necessary. As Mr. Smith remarks, technical considerations rendering series injection essential are not frequently encountered. Multiplicity of injection equipments may render the cost of series equipment prohibitive. Regarding centralization or decentralization, Mr. McWhirter makes a virtue of a necessity with his system; and the examples given by Messrs. Smith and Hallowell are adequate replies.

In injection equipment, the improvement in performance by condenser coupling is referred to by Mr. Smith and Dr. Billig, and is indicated by Table 4 and the equipment particulars in the paper.

In reply to Mr. Szwander, the reactance of a 33-kV, 70-MVA generator would be about 40 ohms at 500 c/s. With a 1% injection voltage per phase (approximately 200 V) the current taken would be of minor importance and would, in any case, be largely reactive.

In reply to Dr. Billig, the input to the machine is direct current. The kVA output of the generator was not measured.

As regards condenser drain, I did not intend, as suggested by Mr. Schiller, to minimize the effect of shunt condensers. These are generally absent in residential areas, and difficulties have been met so far only on networks radiating from one or two

industrial substations. Steps taken were similar to those adopted by Mr. Daines. The possible use of local amplifiers should, however, be borne in mind. I agree with Mr. Szwander in his dislike for power-factor correction by condensers.

In reply to Mr. Hallowell's query on frequencies and channels: The set was designed for four base (or "gate") frequencies and for six operating frequencies, giving, with ten frequencies in all, a total of 24 channels. A separation of 20 c/s is employed, but frequencies corresponding to system harmonics are avoided. With relays responsive only to within $\pm$ 0·5 per cent of rated frequency, a minimum separation of 5 c/s would be necessary. Since, however, the relay frequency-response is influenced by the applied voltage, wider separation than 5 c/s is necessary to reduce the possibility of influence by signals of adjoining frequency.

The method of expressing relay faults in Table 3 is that described by Mr. Daines; the term "operation" refers to the complete performance involving the use of two, and in some cases three, channels. In reply to Mr. Smith, detailed information is not available regarding the relay for the interrupted-phase method, except that it employs a specially designed circuit. From fundamental considerations, however, a two- or three-phase connection would appear necessary. A timed succession of impulses is employed, so that the receiving relay is unlikely to be affected by other system disturbances.

A simple statement of the cost of installing any particular equipment would be of little value without comparable figures for other methods: and a comparison of costs for a large undertaking may prove misleading for different circumstances. The particulars given by Messrs. Jolly and McWhirter are very interesting; and the confirmation of maintenance cost by Mr. Daines is welcome. Mr. Schiller can derive from details given by Mr. McWhirter a capital cost per consumer, excluding relays, of about £1 17s. 6d. on a 20-year repayment basis, to which must be added the equivalent of line rental; for a single parallel-injection equipment the cost will vary according to the installation, but will in many cases amount to a fraction of this.

In reply to Dr. Billig, the signal voltages in Fig. 3 were measured on a network about 3 miles distant, but approximately 16 circuit miles away, from the point of injection. In reply to points raised by Mr. McWhirter, no equipment is included for isolating sections of the system for injection purposes, for this would mean loss of synchronism and operating difficulties. In some of the urgent reconstruction referred to, the voltage control relay had been connected to the section opposite to that in which injection was made. When the sections were coupled, the voltage relay did not take account of voltage drop in the system and signals were therefore weakened. Connection by available pilots to a remote transformer overcame the temporary handicap.

DISCUSSION ON "BUSBAR PROTECTION: A CRITICAL REVIEW OF METHODS AND PRACTICE"*

WESTERN CENTRE, 13TH DECEMBER, 1943

Mr. T. E. Jackson: Built-in testing equipment provides a facility which must inevitably improve the performance of protective gear. This gear is normally dormant, and therefore the most certain way of ensuring that it will operate correctly under fault conditions is to exercise it by means of a test equipment that can be operated as a matter of routine, say, once a shift.

Built-in test-sets are often criticized as further complicating equipment which is considered by some as already too complex, but it must be remembered that complexity is often only an illusion resulting from a rather casual study of a wiring diagram. If, by the addition of telephone jacks, telephone relays, a push-button and a few yards of wire, we can "function" protective gear, omitting only the actual tripping of the breaker, I submit that a slightly more complicated wiring diagram is a very low price to pay.

I would like to know if the authors have been able to apply a built-in "routiner" to busbar protection, and whether they consider that such equipment might be included as a standard feature.

Mr. K. G. Glover: The following points have been met during commissioning tests on busbar-protection equipments: (*a*) There should be no single relay, the accidental operation of which by external mechanical means can trip out a complete section of busbars. (*b*) A fault on a switch spout remote from the busbars is inside the zone of busbar protection; yet the tripping of all the switches in the section may still leave the fault fed from the remote end of the particular circuit concerned. To avoid unnecessary operation of busbar-protective gear for such a fault, the busbar protection should be given a small time-lag sufficient to allow the gear on any individual circuit to operate first. (*c*) To obtain satisfactory overlapping of the zones of protection to cover a fault such as mentioned above, it is desirable that all switches should be provided with accommodation for current-transformers on the busbar side, as well as on the side remote from the busbars. (*d*) I suggest that it would simplify matters considerably for engineers who have to refer to schematic diagrams of busbar protection, if the manufacturers would standardize a simple nomenclature for the various types of scheme, and if the standard number of the scheme used were plainly marked on each diagram.

Mr. C. J. O. Garrard (*communicated*): Designers of busbar-protective systems have tended to seek security against fortuitous operation of the gear, rather by using several independent checks, than by devising gear which is inherently stable under through-fault conditions. I feel that while an independent check upon the operation of the main protective device is essential, it should serve chiefly as a safeguard against unwanted operation caused by damage to the wiring or apparatus or by human agency, such as carelessness in cleaning and so on. The main earth-fault-detecting gear itself should be inherently stable.

One of the best means for assuring stability in balanced-current protective gear is that of balancing the operating current due to the fault against a bias provided by the load or through-fault current. As this principle had been applied with much success to machines, transformers and feeders, it was sought to extend its use to busbars. The essential feature of the resulting system, known as "neutral-bias bus-zone protection," is shown in Fig. A.

The neutral-bias relay has an operating coil and a restraining coil. The operating coil is fed from parallel-connected current-transformers which summate the earth-fault currents in the circuits connected to the busbars. The restraining coil is fed

* Paper by M. KAUFMANN and W. SZWANDER (1943, 90, Part II, p. 273).

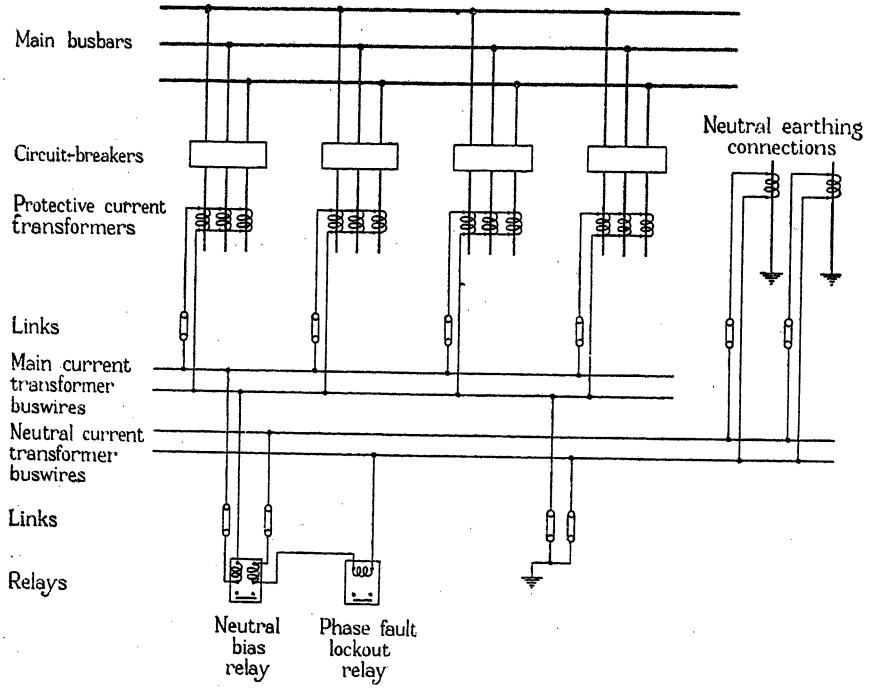


Fig. A

from a current-transformer or transformers, which summate the currents in the neutral connection or connections. If there is an earth fault inside the protected zone, the current in the operating coil is equal to that in the restraining coil and the relay operates. If the earth fault is outside the protected zone, the operating coil carries only the spill current due to the inevitable small inaccuracies of the current-transformers, while the restraining coil carries a current proportional to the earth-fault current; the relay is thus positively restrained from operating.

With a through phase-to-phase fault with no simultaneous fault to earth, there would be a small spill current in the operating coil, but no current in the restraining coil. To maintain stability in all cases, the phase-fault lock-out relay is added; its operating coil is connected in series with the restraining coil of the neutral-bias relay, the contacts of the two relays also being connected in series.

The combination of the two relays is thus stable in all circumstances; if there is sufficient earth-fault current to operate the lock-out relay, there is enough to bias the neutral-bias relay; conversely, if there is no neutral current and thus no bias on the neutral-bias relay, the lock-out relay does not operate.

Several alternative methods of checking may be used in conjunction with this scheme. The simplest is a master relay energized by a second set of current-transformers in the neutral connections. A frame leakage relay may be used, or if the expense of a double set of current-transformers is justifiable, the whole equipment may simply be duplicated, the final tripping contacts of the two equipments being connected in series.

This system offers the advantage over the authors' Fig. 8 in that it requires fewer relays and trips all the circuits connected to the busbars, rather than only those which carry earth-fault current. Compared with Fig. 9, this scheme is much less complicated and is not dependent on the operation of a relay to prevent incorrect operation in the event of a through-fault.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. M. Kaufmann and **W. Szwander** (*in reply*): We fully endorse Mr. Jackson's remarks on the value of built-in testing equipment and agree that it should be a standard feature of all major installations. The example illustrated at the reading of the paper utilizes plugs and jacks; several have been installed and have given great satisfaction to the testing staffs.

In reply to Mr. Glover most of the schemes described in the paper, e.g. those in Figs. 8 and 9, satisfy his condition (*a*). Where it is unavoidable that one relay shall trip all the circuit-breakers of a busbar section, accidental operation by mechanical impulses can easily be prevented by using two identical relays with tripping contacts in series. The use of time delay under the conditions outlined in item (*b*) is unavoidable (see our reply to the discussions at other centres). In many types of switchgear, current-transformers cannot be accommodated on both sides of the circuit-breaker and methods of countering this disability are dealt with in the paper. A standardized nomenclature for the various types of scheme is a desirable aim. The classification adopted in the paper, based on the fundamental principles of operation, is reasonably simple and unambiguous.

Mr. Garrard's scheme in Fig. A combines in one relay the two essential features of discriminating and checking. The net result, however, is two separate schemes because a separate "phase-fault lock-out relay," or the equivalent, is required.

All the schemes described by us for application to new installations can be regarded as inherently stable. But this might not be true when they are applied to existing installations, and then only would Mr. Garrard's opening remarks apply. We advocate checking not as a substitute for, but as an addition to, inherent stability for the purposes he mentions. The impression that the Translay scheme of Fig. 8 trips only those circuits that carry earth-fault current, is incorrect; all the circuits of the faulty busbar-section are tripped. Mr. Garrard's scheme has no affinity with that of Fig. 9, being in the same category as that of Fig. 5(*a*) with which it should properly be compared.

THE EFFECT OF CORONA ON SOLID INSULATING MATERIALS*

By A. MORRIS THOMAS, B.Sc., Associate Member.†

(*The paper was first received* 20*th April, and in revised form* 10*th May*, 1944.)

SUMMARY

The effect of corona impinging on thin insulating materials, i.e. cellulose acetate and varnish cloth, is studied by exposing the material to the discharge in a plane-parallel air-gap, and determining the changes in power factor, permittivity and weight which are produced. The time elapsing before the material is electrically punctured, and the increase of acid content, are also measured. Subsidiary tests such as a comparison of the effect of direct and indirect corona, the differences arising when pure oxygen and pure nitrogen are employed separately as the discharge medium, and visual and photographic studies of the discharge and the measurements of corona onset and extinction voltages are also described. The results are discussed, and it is concluded that direct corona results in a general form of deterioration owing to the absorption and subsequent chemical action of ozone and nitrogen oxides by the material, and at the same time a highly localized or microscopic deterioration which is a consequence of electronic and/or ionic bombardment of the surface and which accounts for the ultimate electrical breakdown. The two forms of deterioration are not related. These conclusions lead to suggestions for tests for assessment of the corona resistance of materials and rule out the possibility of any single test being in itself sufficient for this purpose.

(1) INTRODUCTION

The danger of premature breakdown of impregnated-paper cables and bushings owing to the action of electrical discharges or corona in air spaces existing therein has been known for some years, but it is not generally appreciated that this hazard is likely to arise in any type of apparatus where potentials of a few thousand volts are present. A number of devices have come into use, such as sensitive microphones, radio receivers (interference-measuring sets), specifically designed discharge detectors, which give a sensitive detection of the corona onset, and it has been shown that corona may often occur at voltages less than the rated voltage.

Although an adequate safeguard against corona is its elimination, which is sometimes possible by care in design and the judicious employment of conducting coatings (such as metal coatings, colloidal carbon, and conducting rubber and synthetic resins), yet where, as frequently happens, absolute certainty of the absence of corona cannot be assumed, it is of obvious importance that only resistant materials should be exposed to its action.

It is not only desirable that the electrical and mechanical properties of an insulant subject to corona should not deteriorate, but it is also of consequence that the material should undergo no chemical change such as may produce substances capable of corroding metals. A case in point is the corrosion of copper wire insulated with cellulose acetate when corona is present, and it is possible that this has been the real cause of corrosion observed in other cases, although owing to faulty diagnosis the damage has been attributed to other factors, such as the presence of moisture.

The scope of the work described in the present paper will be seen from the following outline:—

(*a*) Construction of an apparatus of a simple type whereby samples of sheet insulating materials could be exposed to the direct and continuous action of a uniform corona discharge.

(*b*) Determination of the rate of deterioration in properties by systematic non-destructive tests at intervals.

(*c*) Comparison of relative resistance to corona as measured by the exposure time required to cause complete breakdown.

(*d*) Subsidiary tests for the purpose of obtaining an insight into the mechanisms involved.

It should be understood, however, that the aim in view has been not so much to subject the processes involved to a detailed examination as to obtain sufficient data to enable suggestions for satisfactory methods of test to be made.

(2) PREVIOUS WORK

The presence or absence of corona in h.v. apparatus under service conditions is entirely a question of design and manufacturing technique. In a number of cases standard specifications include clauses to ensure its absence, but the methods of test specified are usually of a relatively simple nature and therefore insensitive. Recently more complex and sensitive methods involving discharge detection bridges and radio-interference measurement apparatus have been employed for testing corona in h.v. equipment, and such methods will probably be incorporated in specifications in time to come. One indication of this tendency is the suggestion given in B.S. 833—1939 that an ordinary broadcast receiver can be employed to determine sparking on resistors in ignition systems.

It frequently happens, however, that, on account of spatial limitations, manufacturing difficulties and various other reasons the presence of corona is unavoidable, particularly intermittent corona or sparking which only occasionally occurs as a result of transients. Thus the corona resistance of insulants is of great importance, and some consideration has been given to this subject by certain authorities. As an example, reference may be made to the Royal Aircraft Establishment method of test for the corona resistance of ignition-cable insulation (Specification D.T.D. 2002). So far as is known, the experimental data upon which the test is based have not been published, but details of the method may be of interest. Four turns of a 3-ft length of the cable, after a preheating at 100° C for 5 hours, are wound firmly after cooling on a 1½-in diameter wooden mandrel, which is then inserted in a brass tube of 2¼ in internal bore. A voltage of 25 kV (r.m.s.) is applied between the cable conductor and the brass tube for a period of 2 hours. The cable is considered satisfactory if no signs of splitting or other physical or electrical failure are observed. Another empirical test differing slightly from this is described by Haas.[2] In this case a number of turns of the cable is wound on to a metal cylinder of large diameter and two metal rods parallel to the axis of the latter are placed in contact with the cable. Corona is produced by connecting a source of high voltage between the rods and the cable conductor, and the surface of the insulation is examined at intervals for damage.

More systematic investigations on various insulants have also been made.

Goldman and Wool[1] compared the properties of cable paper, varnished cloth and cellulose acetate before and after being

* Based on Report L/T137 of The British Electrical and Allied Industries Research Association.

† British Electrical and Allied Industries Research Association.

brought into contact with ozone and oxides of nitrogen generated in an ozonizer, a method of test which is based on the assumption that the effect is a consequence of the chemical activity of the gaseous corona discharge products. It was found that the materials deteriorated greatly, cellulose acetate and cable paper losing the greater part of their mechanical and electrical strength after about 12 hours' and varnished cloth after 60 hours' exposure to an ozone concentration of 1%. Especially pronounced was the increase in free acid content in cellulose acetate, e.g. from zero to 2·5%, after 9 hours' exposure, the cause of which was ascribed to decomposition of the material into cellulose and acetic acid. This chemical decomposition was found not to cease with the treatment, but continued to occur whilst the samples were "rested" in a desiccator, and at the same time progressive deterioration in electric strength and power factor was observed. The results of a few additional tests indicated that if the samples were subject to the direct action of the corona the deterioration was accelerated.

Corona discharge on rubber-insulated cables has also been investigated by Paine and Brown.[3] In this case the test was made by placing a straight length of the cable in contact with a flat metal plate, and producing corona by connecting the core and plate to a source of high voltage (60 c/s). By this means, first, a comparative study was made of the behaviour of cables of various designs, ratings and insulation characteristics with respect to the voltage at which corona first started, became visible and finally audible, and, secondly, the effect of the discharge on the power factor of the insulation was determined. The ozone concentration produced was also measured. It is of interest to note that ozone was generated only when the voltage was sufficient to cause disturbances capable of being registered by the discharge detector.

A tentative study of the effect of corona on cellulose acetate sheets and varnished cloth on behalf of the E.R.A. was started by D. E. H. Jones at Queen Mary College in 1935 in two series of tests. The samples were first exposed to the direct action of the discharge in a uniform field, and determinations of the changes in permittivity, power factor, electric strength and, in the case of cellulose acetate, the acetyl content, were made. Secondly, the changes in properties of cellulose acetate caused by exposure to ozone, a mixture of nitrogen oxides, nitrogen peroxide, nitric oxide, nitrous oxide separately, and finally ultra-violet radiation, were investigated. The results of the first series of tests indicated that with a sufficiently high intensity of the discharge failure of the sample occurred within a few hours, although short exposure tests, not exceeding 40 minutes in duration, apparently indicated that the deterioration in power factor and electric strength was not progressive. The second series of tests were designed to ascertain the relative effect of the various factors known to be present in corona discharges. Samples of cellulose acetate were therefore exposed to the possible reactive agents in turn. The results showed that only ozone and nitrogen peroxide were capable of giving rise to the chemical changes caused by an electric discharge, since no effect was observable in any other case.

No useful information was obtained from the acetyl content determinations as the variations were small, but they tended to indicate that the acid content was increased by corona discharge.

The general conclusions drawn from these preliminary tests were, first, that the times of exposure were insufficiently long to enable an insight into the phenomena to be obtained, and, secondly, that it was desirable to determine definitely whether deterioration caused by corona was progressive or whether with low-intensity discharges, for example, a saturation effect supervened.

(3) MATERIALS EMPLOYED IN THE TESTS

(*a*) Commercial cellulose acetate film of nominal thickness 0·005 in.*

(*b*) Two pure high-acetyl cellulose films, one with and one without plasticizer.†

(*c*) Best quality black varnished cloth of nominal thickness 0·005 and 0·010 in.‡

(*d*) Best quality yellow varnished cloth of nominal thickness 0·005 and 0·010 in.

(4) PRELIMINARY CONDITIONING OF SAMPLES

The cellulose acetate samples were preconditioned by heating at 90° C for 24 hours over a drying agent (P_2O_5), and kept in a desiccator until required. The varnished cloth samples were dried at room temperature for a period of three weeks or more before testing. Preliminary tests established that both materials experienced progressive changes in properties when heated at 100° C for some hours, on account of changes in composition and structure. Additional security against uncertainty which might be introduced by ageing effects was provided by utilizing some samples as controls.

(5) INVESTIGATION OF THE EFFECT OF DIRECT CORONA

(5.1) Methods of Test

The preliminary tests by Jones had indicated that the effect of corona could be studied in a convenient manner by placing a sample sheet of the material on the surface of one of the electrodes of a pair forming a horizontal plane-parallel air capacitor and applying an alternating potential sufficient to overstress the air layer between the upper surface of the sample and the top electrode. This principle was used as a basis for the design of the experimental apparatus for the tests reported herein. The rate of deterioration in electrical properties caused by the discharge was observed by periodic measurement of the power factor and permittivity of the sample, and at the same time material changes were indicated by variations in weight and free acid content. Apart from the "rest" pauses necessary for the periodic tests, the samples were exposed to corona continuously either until failure, which was manifested by a spark which punctured the material, or until the power factor increased to 0·06 or more. In the event of breakdown during the exposure, the supply was tripped out automatically and a record of the time made by a gas-filled valve relay, thus avoiding continuous supervision.

All the tests in the present paper were made in a dry atmosphere; the effect of the ambient humidity will be considered in a subsequent paper.

(5.2) Apparatus for Exposure of Samples to Direct Corona

To economize in time, arrangements were made whereby nine samples could be exposed in a dry atmosphere to corona simultaneously, different values of voltage being applied as desired to sets of three. Desiccators of the Scheibler type were employed as enclosures for each sample; they had a hole bored in their upper and lower compartments into which brass leading-in screws were cemented (see Fig. 1), and their lids were provided with a glass tube with stop-cock, which enabled the interior to be evacuated and filled with dry air or any other gas if desired.

In the preliminary E.R.A. investigations (see Section 2) the air-gap between electrode and sample was obtained by use of an annulus of insulating material (hard paperboard). An objection to this method was that stress concentrations probably occurred at the internal edges of the ring, and it was thought advisable to avoid this disturbance and at the same time provide means whereby any thickness of air space, within limits, could be ob-

* Presented by the British Domolac Co., Ltd.
† Presented by Dr. V. E. Yarsley. (Samples A and B, page 552.)
‡ Bitumastic body.

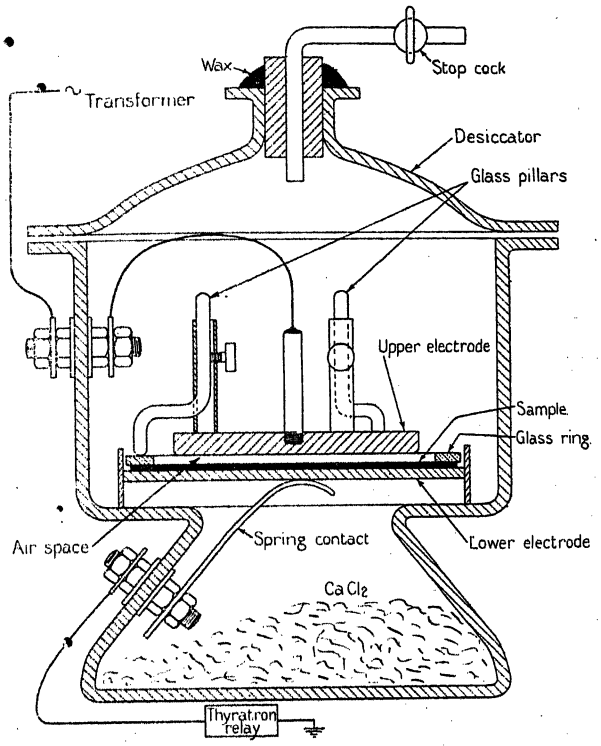


Fig. 1.—Apparatus used for corona exposure. (Not drawn to scale.)

tained if required. The upper electrode was therefore made smaller than the lower electrode and the edges were rounded, leaving a circular flat area of 3 in diameter. Both electrodes were chromium-plated and their surfaces ground plane. Three "double-L" shaped pieces made from 3/16-in diameter glass rod were provided with metal sleeves which fitted into brass uprights fixed on the upper surface of the upper electrode. The feet of these supports rested on a glass annulus which was placed on the sample to keep it flat against the lower electrode; the air-gap spacing was adjustable by grub screws in the metal sleeves and was preset by means of a gauge.

The lower electrode was supported by brass pieces to provide an air space communicating with the lower compartment of the desiccator, and these were made proud of the upper surface in order to keep the sample and glass annulus in position. Other details of the apparatus will be clear from Fig. 1.

Although the sample tended to warp slightly under corona, so causing the lower surface to be out of contact with the electrode, the movement was not pronounced and did not appear to exert any significant influence on the results. To avoid the effect would have necessitated sticking the sample to the metal and on general grounds this was considered to be undesirable.

The possible effect of a drying agent in the test desiccator during the exposure to corona was also considered. Investigation showed that acetic acid vapour which was found to be a product of the decomposition of the cellulose acetate caused by corona was more strongly absorbed by calcium chloride than by cellulose acetate itself, but nevertheless no difference in the results was observed in tests made in air and over calcium chloride as compared with similar tests made in dry air (obtained by evacuating the desiccator and filling through a drying train). As a matter of convenience calcium chloride was therefore employed in the desiccator. It is probable that the diffusion of acetic acid vapour from the air space above the sample is fairly slow and that the consequent changes in concentration at the sphere of action are of no significance.

(5.3) Thickness of Corona Air-Gap

For the preliminary E.R.A. tests (see Section 2) a spacing of 0·089 cm was somewhat arbitrarily selected, but was found to be a convenient value and for this reason was employed in the tests on cellulose acetate. Further consideration indicated, however, that additional security against possible uncertainties arising from small variations in the thickness of the samples and warping might be obtained by the use of a larger gap, and accordingly this was made 0·19 cm for the tests on varnished cloth, but some tests for comparison purposes were made with a 0·089 cm gap.

It is easy to show by simple electrostatic theory that for sample thicknesses of 0·0125 to 0·25 cm, constant electrode spacing, and values of applied voltage less than the corona onset voltage, a variation of sample thickness of 10% will cause a variation of the field strength in the 0·089-cm air layer of 0·9 to 1·7% and in the 0·19-cm layer of 0·4 to 0·8% respectively.

It is also known that the breakdown field strength for spacings of the order under consideration increases with decrease of thickness. It may be assumed that the corona onset voltage of an air layer bounded by parallel surfaces of metal and dielectric respectively is the same as the sparking voltage when both boundary planes are metal. This was more or less confirmed experimentally (Section 7.7). Using the empirical formula given by Stevenson[6] for the breakdown voltage of small air-gaps to calculate the corona onset voltage for the assembly used in the tests, it may be shown that with a sample of dielectric of a given nominal thickness a small increase in thickness will increase the intensity in the contiguous decreased air space by an amount greater than that required to exceed the corona onset voltage corresponding thereto; on the other hand a small decrease in thickness reduces the intensity in the air below this voltage. Hence if the uniformity of the corona is influenced by variations in thickness of the dielectric samples the tendency will be for discharges to occur more readily on the thicker parts of the sample.

(5.4) Power Factor and Permittivity Measurements

These measurements were made by quickly removing the sample from the corona desiccator and assembling it between special electrodes in another desiccator, which contained a plane brass disc of 4 in diameter serving as the h.v. electrode, and an upper brass electrode, also circular, surrounded by an annulus, the combination forming the measurement electrode with guard ring. The diameter of the measurement electrode was 3 cm in the tests on cellulose acetate but was increased to 6·2 cm for the varnished cloth samples. The circular area exposed to corona was 7·6 cm diameter, so that in the latter tests an average value for almost the entire affected area was obtained. The upper electrode was applied with a pressure equivalent to 300 g/cm^2, which preliminary tests established as being necessary to make the measurements reproducible to within 1%. The accuracy of the permittivity measurements was limited by local variations in thickness which were of the order of ± 5%, but contact effects were reduced to some extent by inserting 6-mil tinfoil between the sample and the lower electrode.

A Schering bridge was employed for the measurements, which were made at a frequency of 800 c/s, and the estimated accuracy was of the order of 0·01% for power factor and 1% for capacitance.

(5.5) Determination of Acid Value

It was at first proposed to determine the change in acetyl content of the cellulose acetate samples caused by the corona, but it was found that the samples became partly or wholly insoluble in acetone, which rendered the usual method inapplicable. The free acid content was therefore determined instead by extraction with pure ethyl alcohol. The sample of cellulose acetate, weighing about 1 g, was cut into small pieces and placed in a conical

flask with 10 ml of absolute alcohol. A reflux condenser was fitted to the flask and the contents were heated to just below boiling for one hour. After cooling, the extracts was decanted into a small flask and the residue washed twice with absolute alcohol. The washings were added to the extract and titrated with alcoholic caustic potash, using phenolphthalein as indicator. As a check test, samples of dried cellulose acetate were allowed to absorb acetic acid vapour by placing them in a closed desiccator containing a small dish of the liquid, the quantity absorbed being determined by the increase in weight. The absorbed acid was then extracted by the method described. It was established from the values obtained on four samples that the alcohol extraction removed on the average 91% of the total free acid content. If water was used instead of alcohol only 70% of the total free acid was extracted.

The free acid content of the varnish cloth samples was determined in a similar manner except that a mixture of alcohol and benzene instead of pure alcohol was employed.

All the acid-content determinations were made on the samples after removal of the outer margin, leaving a disc of material of about 3 in diameter, the entire surface of which had been in direct contact with the discharge. The acid-content values tabulated were made comparative by correcting them to correspond to 1 g of the material.

(6) EXPERIMENTAL RESULTS

Tests on cellulose acetate samples were made with applied voltages of 4 000, 3 000 and 2 000 volts. The tests were not in all cases continued until breakdown of the sample, since increase of power factor to about 0·06 or more was considered to constitute failure.

The variation in power factor and permittivity during the course of the exposure to direct corona is shown in graph form in Fig. 2. When the sample failed by puncturing, the power factor and permittivity test was made on the undamaged part.

Three samples to serve as controls were kept in a desiccator over $CaCl_2$ for a long period; the initial and final values of power factor and permittivity are given in Table 1. It will be seen that

Table 1

TESTS ON SAMPLES NOT SUBJECT TO CORONA AND KEPT IN DESICCATOR OVER $CaCl_2$

Sample No.	Time in desiccator, hours	Initial values		Final values	
		Power factor	Permittivity	Power factor	Permittivity
1	192	0·0235	3·37	0·0213	3·24
2	144	0·0227	3·31	0·0217	3·15
3	144	0·0227	3·46	0·0225	3·27

the power factor and permittivity both show small decreases after prolonged exposure to a dry atmosphere.

The initial and final values of power factor, permittivity and change of weight of cellulose acetate caused by the corona, together with the acid values at the end of the test, are summarized in Table 2. The acid values given have been corrected by subtracting 0·15 ml as found in blank tests. It will be noted that samples 7, 8, 9 show a small improvement in properties similar to that found for the control tests given in Table 1.

Some tests were also made on two special cellulose acetate films which were identified as follows:—

Sample A. High-acetyl film (plasticized): Acetyl value of acetate used = 56·6%. Plasticizer 25%.

Sample B. Triacetate film (unplasticized): Acetyl value = 61·6%.

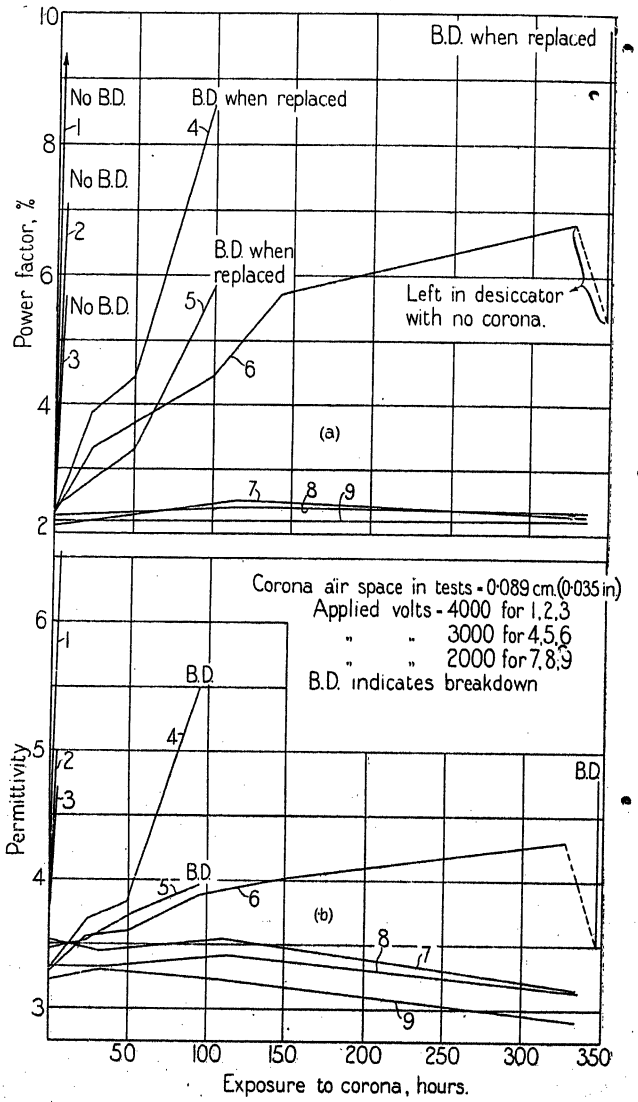


Fig. 2.—Variation of power factor and permittivity with time with different corona intensities.

The results are given in Table 3. The initial low power factor of sample B is worthy of note, and, in addition, the fact that high-acetyl cellulose films are somewhat more resistant to the action of corona than ordinary films so far as increase of power factor and permittivity is concerned.

The method of test for the varnished cloth differed slightly from the above in that the voltage at first applied was relatively low but was then suitably increased in order to increase the intensity of the discharge and so to accelerate the deterioration.

Fig. 3 shows the changes in permittivity, power factor and weight of three samples of 5-mil black varnished cloth as a result of exposure to corona. A voltage of 4 750 (r.m.s.) was applied for 35 hours continuously, and then raised to 5 000 volts. Sample No. 6 failed by puncturing after 59 hours. After 46 hours' rest in a desiccator with calcium chloride, samples Nos. 4 and 5 showed some regain in properties. After replacing in position and re-applying 5 000 volts, the deterioration continued, sample No. 4 puncturing after another 41 hours' exposure. It will be noted that the changes in power factor, permittivity and weight were closely correlated.

Fig. 4 shows the changes which occurred with 10-mil black varnished cloth. A voltage of 5 000 was first applied and main-

Table 2

SUMMARY OF RESULTS OF CORONA TESTS ON CELLULOSE ACETATE

Sample No.	Applied volts (r.m.s.)	Exposure to corona, hours	Breakdown, if any	Initial values		Final values		Acid value, ml N/10 KOH referred to 1 g	Change of weight during test, g	Equivalent weight of acetic acid from acid value, g
				Power factor	Permittivity	Power factor	Permittivity			
1	4 000	4	No	0·0268	3·87	0·0597	4·96	7·0	+ 0·018	0·042
2	4 000	4	No	0·0255	3·63	0·0575	4·96	7·2	+ 0·033	0·043
3	4 000	4	No	0·0258	3·65	0·0701	4·69	7·5	+ 0·028	0·045
4	3 000	96	Yes	0·0225	3·32	0·0838	5·47	7·1	+ 0·046	0·043
5	3 000	96	Yes	0·0238	3·48	0·0560	3·97	3·2	+ 0·027	0·019
6	3 000	327	Yes	0·0228	3·28	0·0996	4·81	5·15	+ 0·019*	0·031
7	2 000	336	No	0·0229	3·36	0·0230	3·15	0·05	− 0·003	—
8	2 000	336	No	0·0223	3·36	0·0224	3·17	Nil	− 0·004	—
9	2 000	336	No	0·0226	3·32	0·0222	2·92	Nil	− 0·004	—

* This sample was left for 40 hours in desiccator with no corona after 327 hours' exposure, and it failed 3 minutes after being replaced on test.

Table 3

EFFECT OF CORONA ON HIGH-ACETYL CELLULOSE ACETATE FILM WITH AND WITHOUT PLASTICIZER

Sample	Applied volts (r.m.s.)	Exposure to corona, hours	Breakdown, if any	Initial values		Final values	
				Power factor	Permittivity	Power factor	Permittivity
A 1	4 000	4	No	0·0215	3·58	0·0416	4·43
2	4 000	4	No	0·0212	3·48	0·0236	3·69
3	4 000	4	No	0·0202	3·44	0·0546	4·35
4	4 000	1½	Yes	0·0211	3·35	0·0683	4·27
B 1	4 000	3	Yes	0·0127	3·38	0·0248	3·94
2	4 000	4	No	0·0138	3·41	0·0210	3·87
3	4 000	4	No	0·0132	3·40	0·0403	3·65
4	4 000	4	No	0·0130	3·40	0·0211	3·77

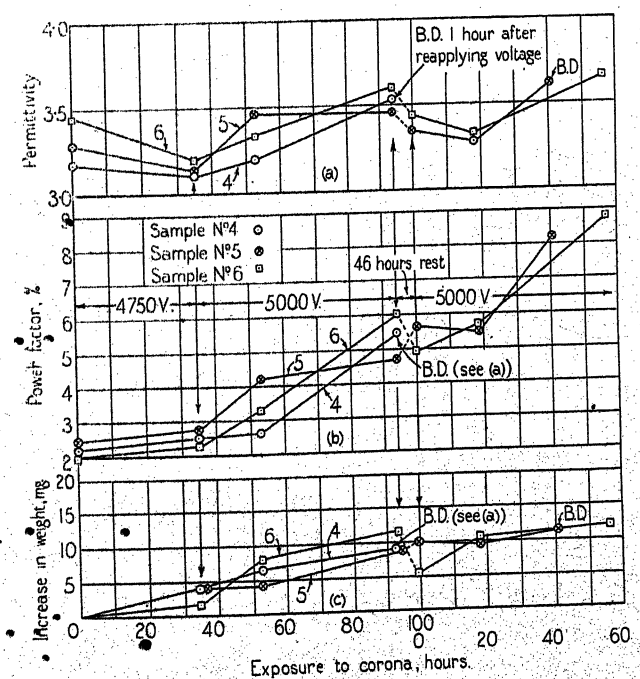


Fig. 3.—Effect of corona on 5-mil black varnished cloth. (Corona layer above sample = 0·19 cm.)

tained for 69 hours on No. 2 and for 131 hours on Nos. 1 and 3, but no appreciable change occurred except a small decrease in permittivity and an increase in weight. At the end of this period the voltage was increased to 5 500 volts, and this caused a rapid deterioration in properties within 4 hours.

The results of the tests on yellow varnished cloth as shown in Figs. 5 and 6 are similar except that the deterioration is slightly more rapid. The 5-mil samples (Fig. 5) were tested with 5 000 volts. Sample No. 12 failed by puncturing after 16 hours, sample No. 10 was exceptional in that it gave a high increase in power factor and permittivity when rested for 17 hours after 13½ hours' exposure. Sample No. 11 was deemed to have failed by acquiring a high power factor after 3¼ hours' exposure. Of the 10-mil samples of yellow varnished cloth (Fig. 6), sample No. 7 was tested with 5 000 volts for 22 hours, and samples Nos. 8 and 9 with this voltage for 33 hours, without appreciable changes occurring except some increase of weight. At the end of these periods the voltage was raised to 5 500 volts, when deterioration occurred within 4 hours, the samples acquiring a high power factor. The exposure at these voltages was not continuous, since at the periods indicated on the curves there were periods of rest of a few days when a relatively small regain of properties occurred.

A summary of the final measurements, including acid values made on the varnished cloth samples, is given in Table 4, and may be compared with measurements made on the control samples, which were kept over calcium chloride but not exposed

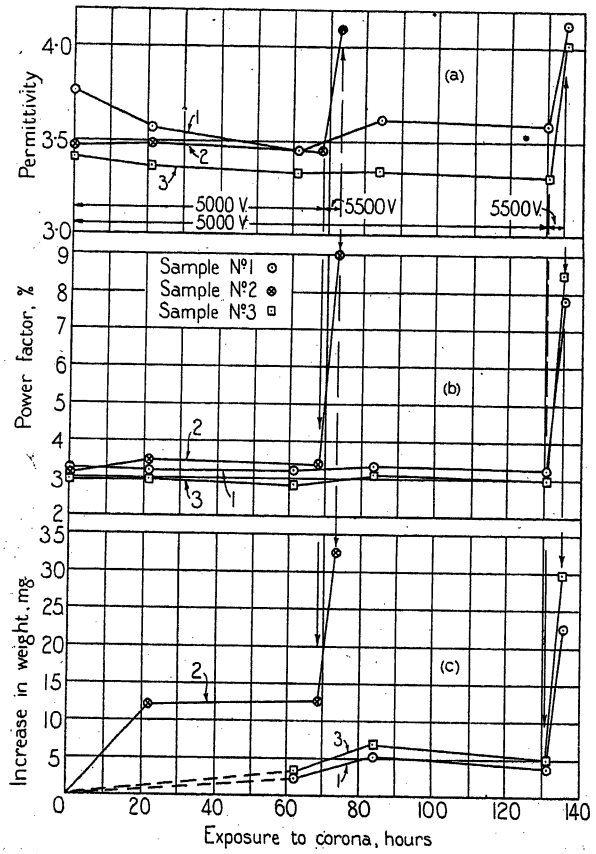


Fig. 4.—Effect of corona on 10-mil black varnished cloth. (Corona layer above sample = 0·19 cm.)

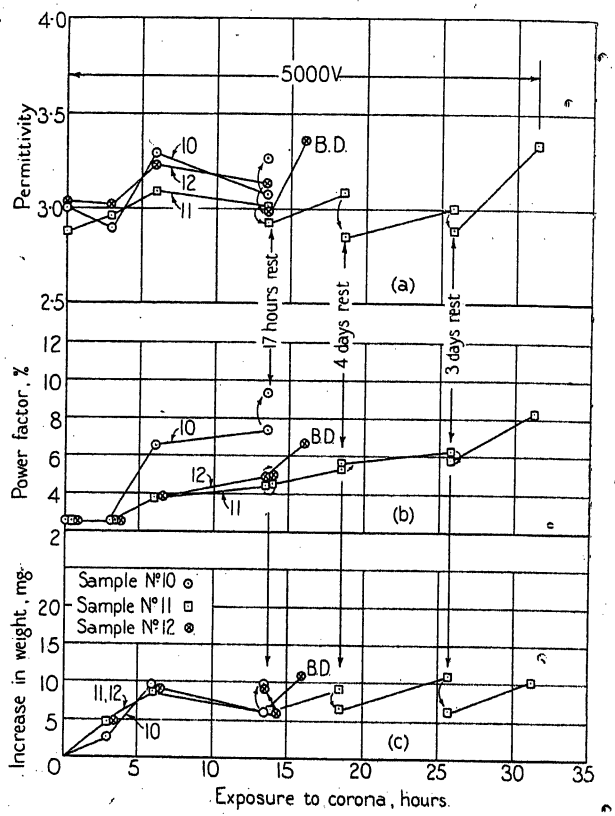


Fig. 5.—Effect of corona on 5-mil yellow varnished cloth. (Corona layer above sample = 0·19 cm.)

to corona, and which are given in Table 5. The period between these control tests extended over a number of days, and the results are given as percentage change per day. It will be seen

Table 4

MEASUREMENTS ON VARNISHED CLOTH AFTER EXPOSURE TO CORONA

Material	Sample No.	Final values of—			Final acid values, ml N/10 KOH, referred to 1 g
		κ	tan δ	Increase in weight mg	
0·005-in black varnished cloth	4	3·54	0·0548	7·8	2·5
	5	3·61	0·0823	12·1	2·6
	6	3·66	0·0885	13·2	2·8
0·010-in black varnished cloth	1	4·12	0·0777	22·6	3·0
	2	4·10	0·0896	32·6	2·2
	3	4·02	0·0845	29·7	2·6
0·005-in yellow varnished cloth	10	3·26	0·0927	9·6	2·7
	11	3·34	0·0836	10·2	—
	12	3·35	0·0668	11·1	2·6
0·010-in yellow varnished cloth	7	5·08	0·0117	49·8	2·8
	8	5·02	0·0111	63·2	2·4
	9	4·45	0·0949	45·9	2·7

that the change in properties of the samples during the corona tests on account of ageing are negligible compared with the changes directly attributable to the action of the corona, and, in

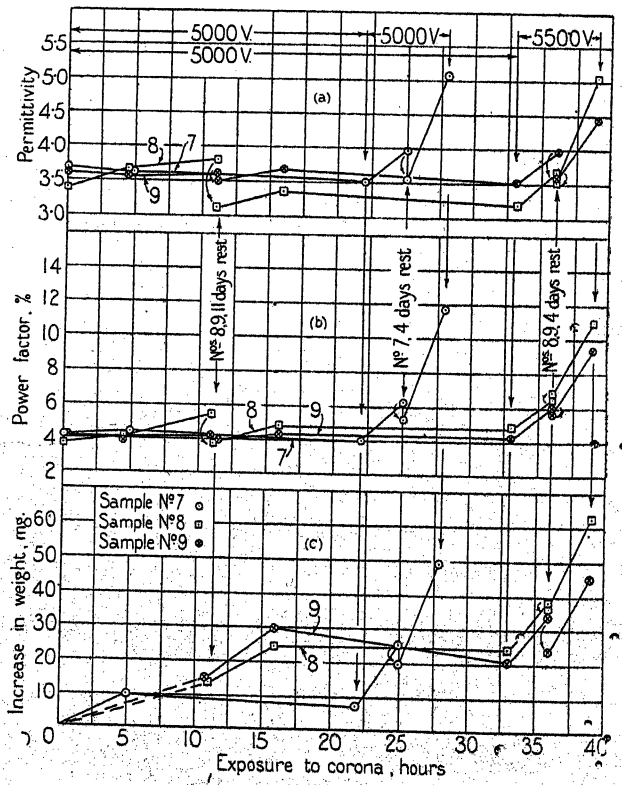


Fig. 6.—Effect of corona on 10-mil yellow varnished cloth. (Corona layer above sample = 0·19 cm.)

Table 5

CONTROL TESTS

Material	Sample No.	Initial values of—			Percentage change in properties per day in—			Final acid value, ml N/10 KOH, referred to 1 g
		Permittivity	Power factor	Weight, g	Permittivity	Power factor	Weight	
0·005-in black varnished cloth	13	3·42	0·0250	1·4651	− 0·1	− 0·06	− 0·001	1·7
	14	2·78	0·0207	1·4415	− 0·04	− 0·02	− 0·001	2·0
	15	3·31	0·0276	1·4679	+ 0·02	− 0·22	− 0·002	1·9
0·010-in black varnished cloth	16	3·60	0·0321	2·9490	− 0·32	− 0·44	− 0·01	2·2
	17	3·17	0·0231	2·8549	− 0·40	+ 0·56	− 0·01	1·7
	18	3·68	0·0294	2·8541	− 0·50	− 0·25	− 0·09	1·8
0·005-in yellow varnished cloth	19	3·23	0·0337	1·7614	− 0·09	− 0·12	− 0·01	2·7
	20	3·28	0·0340	1·7413	− 0·09	− 0·11	− 0·003	3·0
	21	3·26	0·0321	1·7486	+ 0·002	− 0·02	− 0·006	2·8
0·010-in yellow varnished cloth	22	3·42	0·0373	3·0160	− 0·11	− 0·08	+ 0·01	2·8
	23	3·63	0·0405	3·1429	− 0·04	− 0·02	+ 0·01	2·6
	24	3·34	0·0398	3·0970	+ 0·02	− 0·06	+ 0·02	2·6

most cases, are probably due to a slight improvement in properties consequent on further gradual drying.

(7) SUBSIDIARY TESTS

(7.1) The Effect of Direct Corona on Black Varnished Cloth and Cellulose Acetate Compared

In order to enable a direct comparison to be made between the results obtained in the present tests and those on 5-mil cellulose acetate film, samples of 5-mil black varnished cloth were exposed to corona in the arrangement employed previously, i.e. the air gap of 0·089 cm was used.

The two sets of results obtained are summarized in Table 6, the values for cellulose acetate being reproduced from Table 2, the acid values being corrected by subtracting the mean acid value of the untreated control samples.

It will be observed that, taking into account the different exposure times, the cellulose acetate is less affected by corona so far as changes in power factor and permittivity are concerned, although it gives greater increases in acid value and weight.

Samples of 5-mil black varnished cloth when exposed to corona as above with an applied voltage of 4 000 volts were found to fail by puncturing in a few seconds. Cellulose acetate films of the same thickness in the previous work withstood this voltage for several hours.

(7.2) The Effects of Direct and Indirect Exposure to Corona Compared

A comparison of the effect of corona impinging directly on to the surface of the sample with that produced merely by the gaseous discharge products was carried out by means of the electrode system shown in Fig. 7. A disc of aluminium gauze was cemented between two glass rings which rested on a sample disc of the material. Another sample disc of a smaller diameter rested on the top of the gauze, and on this was placed a plane metal disc with a thin strip of tinfoil folded round the edge of the upper sample so that the gauze was connected electrically with the h.v. terminal. The lower sample was exposed to direct corona formed in the intermediate air space, whilst the upper sample was simultaneously exposed to indirect corona, i.e. only to the gaseous discharge products.

The whole arrangement was assembled in a closed desiccator containing calcium chloride as in the ordinary tests.

Owing to the heating effect of the corona, the aluminium gauze bulged downwards slightly, making the thickness of the air layer indefinite, consequently somewhat lower voltages were required than in the previous tests.

The results of tests on 10-mil yellow varnished cloth are shown in Fig. 8. A voltage of 3 200 volts was first applied, which was increased to 3 600 volts after 24 hours, the latter voltage being maintained for a further 46 hours.

Table 6

COMPARISON OF RESULTS ON 0·005-IN BLACK VARNISHED CLOTH AND CELLULOSE ACETATE FILM

(*Thickness of Air Layer above Sample* = 0·089 cm)

Material	Sample No.	Initial values of—			Applied volts (r.m.s.)	Period of exposure, hours	Final values of—			Increase in acid value due to exposure, ml N/10 KOH, referred to 1 g
		Permittivity	Power factor	Weight, g			Permittivity	Power factor	Weight, g	
0·005-in black varnished cloth	25	3·24	0·0239	1·4393	3 000	4	4·43	> 0·135	1·4606	1·2
	26	3·42	0·0256	1·4334	3 000	4	4·89	> 0·120	1·4538	1·7
	27	3·29	0·0247	1·4671	3 000	4	4·08	0·104	1·4884	1·3
0·005-in cellulose acetate film	4	3·32	0·0225	1·726	3 000	96	5·47	0·0838	1·772	6·8
	5	3·48	0·0238	1·695	3 000	96	3·97	0·0560	1·722	2·9
	6	3·28	0·0228	1·698	3 000	327	4·81	0·0996	—	4·8

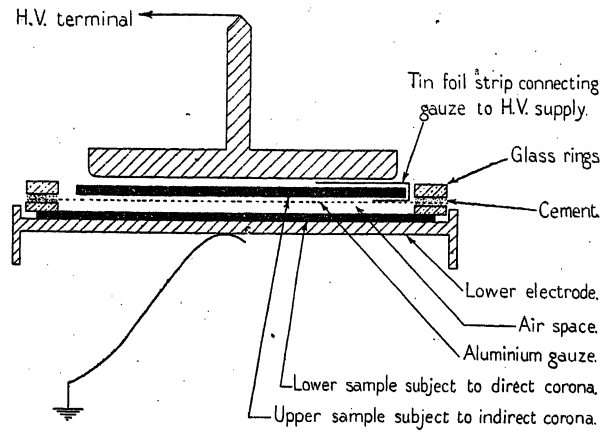


Fig. 7.—Method of comparing the effects of direct and indirect corona.

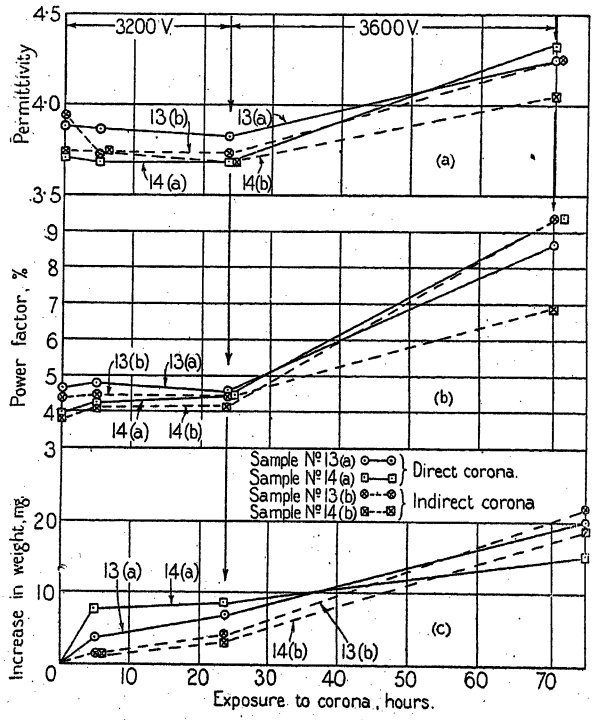


Fig. 8.—Effects of direct and indirect corona on 10-mil yellow varnished cloth.

The samples were tested in pairs 13 (*a*), (*b*) and 14 (*a*), (*b*) respectively. Similar tests on 10-mil black varnished cloth were carried out with the results shown in Fig. 9, the two pairs of samples being 15 (*a*), (*b*) and 16 (*a*), (*b*) respectively. In this case the regain in properties after removing the voltage was measured up to a period of 30 days. It is to be noted that the (*b*) samples were of a smaller diameter than the (*a*) samples, and therefore the increases of weight of the two sets of samples are not strictly comparable.

The results indicate that deterioration as estimated by increases in power factor and permittivity is mostly, if not entirely, due to the effect of the corona gases, any damage to the sample which may be caused by bombardment of the surface by electrons or ions not being made manifest by these criteria.

(7.3) The Effect of Corona in Oxygen and Nitrogen

Samples of cellulose acetate and 10-mil yellow varnished cloth

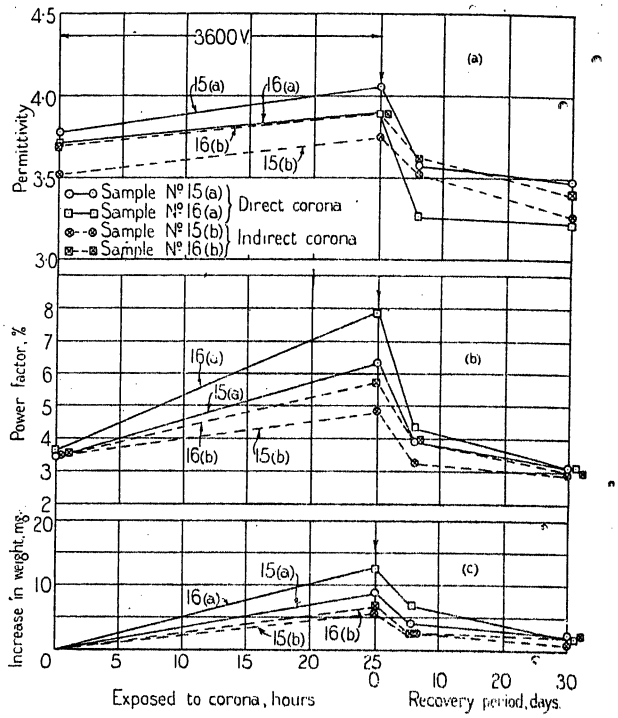


Fig. 9.—Effects of direct and indirect corona on 10-mil black varnished cloth.

were exposed to the action of direct corona in the same apparatus as used for the tests described in Section 5, except that the glass container (desiccator) was evacuated after the samples were placed in position and then filled with oxygen or nitrogen taken from a cylinder. The pressure of the gas was made slightly greater than atmospheric and then equalized by a momentary opening of the stop-cock. For the cellulose acetate samples a corona layer of 0·089 cm was used and a voltage of 4 000 volts was applied for 4 hours. Power factor, permittivity and weight tests with a final acid value determination were made before and after exposure. The results are given in Table 7. In the case of the varnished cloth samples in oxygen the corona layer was 0·19 cm and 5 500 volts were applied for 27 hours with intermediate periods of rest. In nitrogen 5 500 volts was applied for 10 hours and then 6 000 volts for 11 hours after a "rest" interval. The results are shown in Figs. 10 and 11.

A comparison of the results for cellulose acetate with those obtained in air as given in Table 2 shows that the power factor values produced by corona in oxygen were practically the same as those obtained in air, but the permittivity, change of weight and acid value figures were definitely lower. It is to be seen that corona in nitrogen caused no appreciable change.

The results of the tests on varnished cloth show that the deterioration due to corona in pure oxygen occurred with an applied voltage of 5 500 volts as in air but at a slower rate, and the increase in weight corresponding to the same final power factor (4·8–5·4%) was roughly the same. On the other hand, there was again no appreciable change in power factor or permittivity due to corona in nitrogen, but there was a small loss of weight. At the same time, however, puncture of both samples occurred after periods of 9 and 21 hours respectively, thus demonstrating the existence of some form of progressive deterioration which is not indicated by power loss tests.

The samples tested in oxygen developed white, chalky areas, whereas those in nitrogen became a light uniform grey, with no local patches.

Table 7

EFFECT OF CORONA ON CELLULOSE ACETATE IN PURE OXYGEN AND NITROGEN

Sample No.	Test gas	Applied volts (r.m.s.)	Exposure to corona, hours	Breakdown, if any	Initial values		Final values		Acid value, ml N/10 referred to 1 g	Change of weight during test, mg
					Power factor	Permittivity	Power factor	Permittivity		
10	O_2	4 000	4	No	0·0213	3·12	0·0617	4·05	3·3	+ 4
11	O_2	4 000	4	No	0·0235	3·28	0·0741	4·07	2·6	− 2
12	N_2	4 000	4	No	0·0220	3·30	0·0244	3·60	0·1	− 6
13	N_2	4 000	4	No	0·0241	3·77	0·0263	3·83	0·1	Nil
14	O_2	4 000	4	No	0·0255	3·94	0·0531	4·19	1·6	Nil
15	O_2	4 000	4	No	0·0244	3·78	0·0465	4·02	1·4	− 1

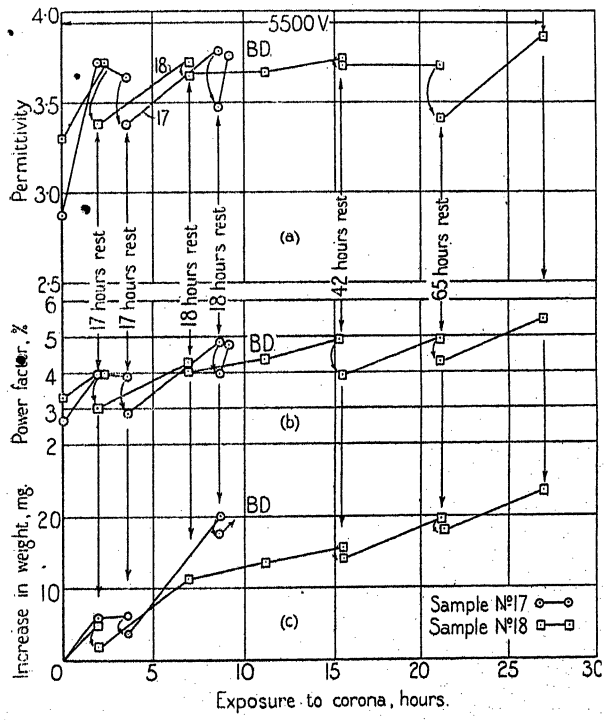


Fig. 10.—Effect of corona in oxygen on 10-mil yellow varnished cloth. (Corona layer above sample = 0·19 cm.)

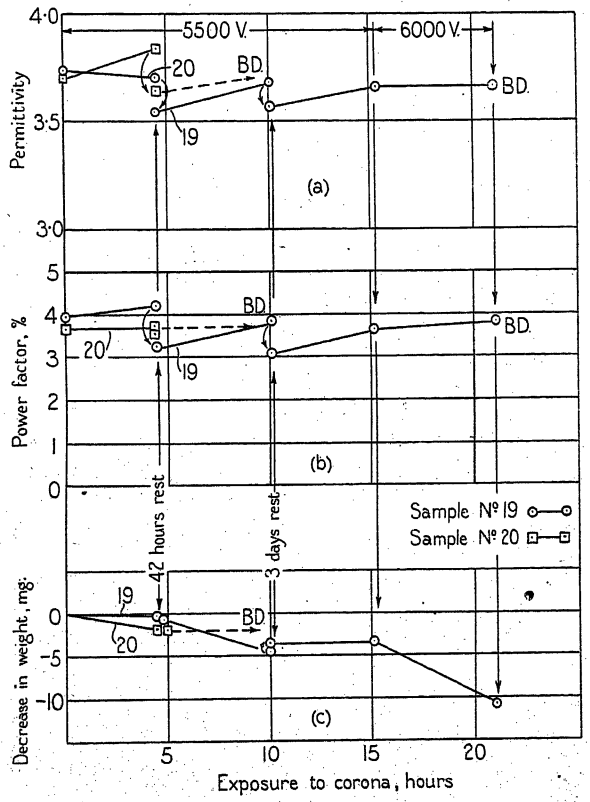


Fig. 11.—Effect of corona in nitrogen on 10-mil yellow varnished cloth. (Corona layer above sample = 0·19 cm.)

(7.4) Visual Changes Caused by Corona

After the exposure of cellulose acetate to corona the material was found to have warped somewhat as if it had increased in volume, and white translucent areas appeared on the previously transparent surface. A faint odour of acetic acid could be detected and the brass electrode used for the power factor and permittivity tests invariably became discoloured after contact with the sample.

The surface of the varnished cloth samples was also altered by corona. After exposure sufficient to cause an appreciable change in properties, the varnished cloth was found to have lost its polish and become dull on the exposed side, and a few dull patches were also to be observed on the side next to the earthed electrode, indicating that probably some discharge occurred on this side at areas not in direct contact with the metal.

A typical appearance of a sample after exposure is illustrated in Fig. 12, which was observed in the case of 5-mil black varnished cloth sample No. 4, Table 4. This sketch is drawn half full size. The two different types of surface change shown in the sketch are quite distinct and indicate the existence of two separate processes originated by the discharge.

The samples subject to only indirect corona as in Section 7.2 became slightly dulled over a more or less irregular area, but the small darker circular patches indicated in Fig. 12 were absent.

(7.5) Power Factor and Permittivity Tests on Cellulose Acetate with known Free Acetic Acid Content

Two discs of cellulose after drying as before were subjected to an atmosphere saturated with acetic acid vapour. The samples gradually increased in weight due to absorption of the vapour, and power factor and permittivity tests were made at intervals. After power factor values had increased to over 6%, the samples were exposed in a desiccator over $CaCl_2$ and gradually their weight decreased owing to loss of the acetic acid. Thus the

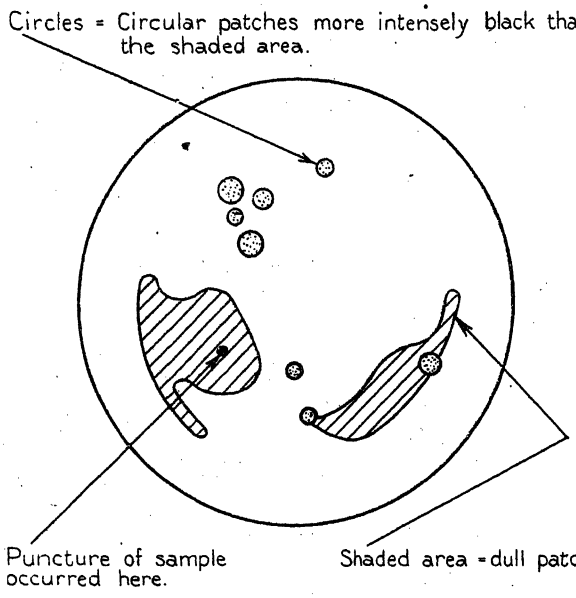


Fig. 12.—Appearance of surface of sample No. 4 after exposure to corona.

samples were taken through a cycle and the results are shown in Fig. 13. The acetic acid contents of the samples were corrected to the equivalent for 1 g of sample and thus correspond to the acid values given in Table 2, and for comparison these values are also shown in Fig. 13 by circles.

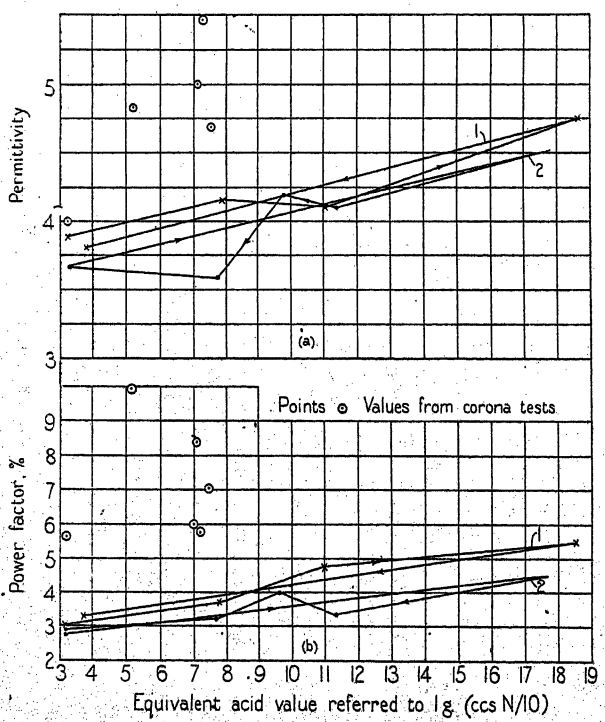


Fig. 13.—Variation of power factor with free acetic acid content.

It is clear that the increases of power factor and permittivity caused by corona are considerably greater than the values to be anticipated on the assumption that they are due solely to absorption of acetic acid produced by decomposition.

(7.6) Visual and Photographic Investigation of the Corona Discharge

It was suspected from the somewhat erratic nature of the results that, notwithstanding the plane-parallel air layer employed, non-uniformities in the corona discharge were present owing perhaps to minute imperfections in the surface of the samples. To investigate this a method was developed whereby the discharge was produced in an air space bounded on one side by a glass plate, the arrangement being similar in principle to that described by Robinson[5] for the investigation of ionization in voids between layers of cable insulation. The apparatus used is shown in Fig. 14, which is almost self-explanatory. A cellulose acetate

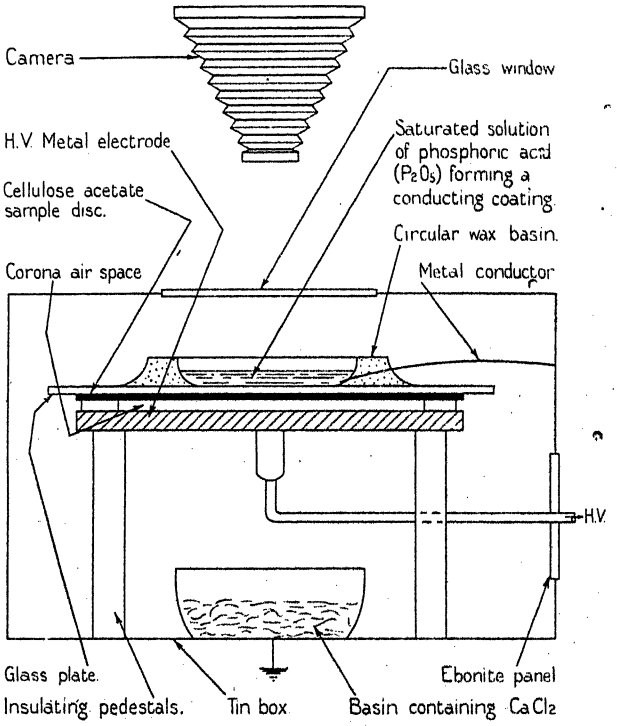


Fig. 14.—Arrangement for visual and photographic examination of corona discharge. (Not drawn to scale.)

sample, being transparent, can be placed directly under the glass plate as in the Figure, so that the discharge is bounded by the material and a metallic surface, the conditions present in the corona tests. With varnished cloth this cannot be done, and the material, being opaque, has to be placed on the lower metal surface, the discharge now being bounded by dielectric surfaces on both sides. The air-gap spacings were 0·127 cm for cellulose acetate and 0·19 cm for varnished cloth. The discharge was observed visually or photographed from above in the direction parallel to the applied electric field.

When a sufficiently high voltage was applied blue-green sparks were observed. They had the appearance of a large number of points of light in continual motion very similar to Brownian movement. As the voltage was increased the points of light became more numerous and ultimately the entire area was more or less uniformly illuminated.

The value of the applied voltage used was just above the value required to give a dense and uniform distribution of sparks when observed visually. Although an additional factor was introduced into these tests owing to the presence of the glass electrode, subsequent oscillographic tests indicated that the character of the discharge was similar to that when a metal electrode was employed

and thus the information yielded by these tests is probably generally applicable.

The whole area of the discharge under the liquid layer was photographed approximately full size. Hypersensitive panchromatic films were used with an exposure of 30 seconds, using a small camera with an *f*/3·8 lens.

Visually no concentration of the discharge can be detected, but the photographs showed very clearly the development of local discharge concentrations and in the case of cellulose acetate the outline of areas caused probably by the sample warping. Two typical photographs obtained with 5-mil varnished cloth are reproduced in Figs. 15 and 16 to illustrate the phenomenon.*

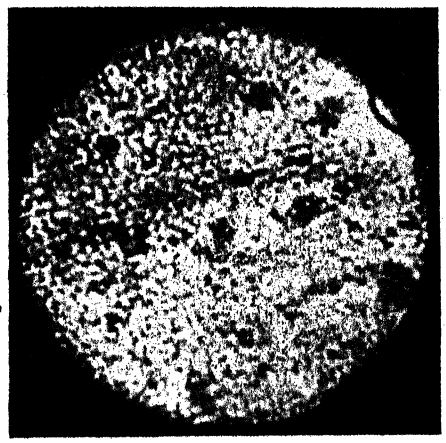


Fig. 15.—Photograph of discharge on 0·005-in black varnished cloth immediately after switching on. Applied voltage 7 800 volts. (The black curved line in the upper right-hand corner is a part of the wire making contact with the liquid on the upper glass surface.)

Directly after switching on there is apparently a tendency for the statistical distribution of the sparks to be related to the pattern of the cloth (see Fig. 15). This shows up in the photograph owing to the 30-second exposure, but it cannot be observed visually as the persistence of vision is too short. After some time this statistical distribution tends to become more uniform, but spark concentrations at one or more particular points now appear (see Fig. 16).

It is supposed that these localized concentrations are the manifestation of microscopic disintegration which finally leads to breakdown of the sample.

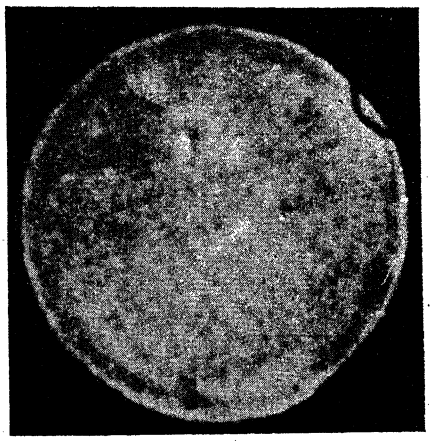


Fig. 16.—Photograph of discharge on same area as in Fig. 15. Taken after 6½ hours' continuous exposure.

(7.7) Determination of Corona Onset and Extinction Voltages

When discharge occurs in an air-gap of the type and dimensions employed, the current transient is relatively large and does not require any special type of detecting circuit such as is necessary to give an indication of discharges in minute voids. In the present instance observations were made with a low-voltage sealed-off cathode-ray oscilloscope, with the circuit shown in Fig. 17. The potential drop across a non-inductive resistor R was applied direct to the deflecting plates, and the onset of

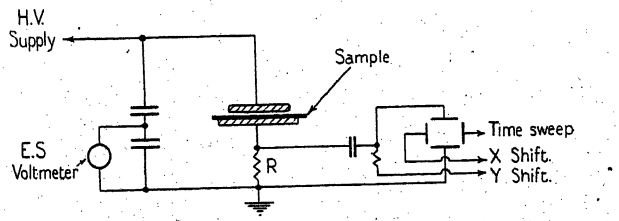


Fig. 17.—Circuit for determination of corona threshold voltages.

corona as the voltage was raised was clearly indicated by a rapid transient which occurred close to the instant when the current would otherwise pass through zero, this instant of course corresponding in time with the applied crest voltage. Corona extinction voltages were obtained by decreasing the applied voltages and noting when the transient discharge currents vanished. The mean values obtained from five tests in each case are given in Table 8, the individual tests showing deviations from the mean of which the largest amounted to about 10%.

Measurement showed that the peak factor of the applied voltage

Table 8

CORONA STARTING AND EXTINCTION VOLTAGES

Electrode system	Air-gap	Sample	Applied volts (peak)	
			Onset	Extinction
As used in corona exposure tests (Section 5.2)	0·19 cm	5-mil black varnished cloth	7 150	6 500
		10-mil black varnished cloth	7 300	6 550
		5-mil yellow varnished cloth	6 890	6 450
		10-mil yellow varnished cloth	6 810	6 450
As used with glass electrode in visual and photographic tests (Section 7.6)	0·19 cm		8 770	7 950
			8 330	7 730

Any possibility that the concentrations were due to the glass surface was ruled out by taking another photograph after rotating the glass 90° with respect to the dielectric sample.

* The photographs have suffered loss of contrast and definition in reproduction.

was 1·7,* so that the crest voltage corresponding to 5 000 volts r.m.s. as used in the tests reported in Section 6 was 8 500 volts, i.e. roughly 25% more than the extinction voltages. Certain other points of interest with respect to the discharge characteristics observed will be discussed in another paper since, although important, they have no immediate relevance to the present problem. It deserves mention, however, that oscillograms of the current wave form somewhat unexpectedly gave no indications of asymmetry notwithstanding the asymmetrical nature of the surfaces bounding the discharge space.

(8) DISCUSSION OF TEST RESULTS

(8.1) General

It is proposed to employ for convenience the terms "dielectric-loss deterioration" and "electric-strength deterioration" to denote the two distinct processes which appear to be engendered by exposure to corona, these terms being defined as follows:—

Dielectric-loss deterioration denotes the change which is made manifest by correlated increases in the permittivity and power factor of the material.

Electric-strength deterioration denotes the change owing to which the material fails electrically by being punctured when exposed to direct corona.

Chemical deterioration, as reflected in development of acidity, and mechanical deterioration are separate aspects which are outside the scope of the present paper.

The results of the tests employing exposure to direct corona show that with varnished cloth, dielectric-loss deterioration becomes perceptible in a few hours when the applied voltage exceeds the corona extinction voltage by about 25%. Cellulose acetate shows similar behaviour. This deterioration is correlated with an increase in weight. During "rest" periods some regain of properties occurs with corresponding loss of weight. The regain, so far as can be judged, is practically complete with a short exposure followed by a long "rest" period, but with long exposures and higher corona intensities the improvement after a "rest" of many days' duration is small.

Chemical tests indicate that exposure to corona causes cellulose acetate to decompose with production of acetic acid and presumably cellulose, but the power-factor and permittivity values are substantially higher than are to be expected from the free acid content. With varnished cloth the increase of free acid content is relatively small and is also not apparently sufficient to account for the dielectric-loss deterioration or the increase in weight.

The most reasonable explanation of these facts is that dielectric-loss deterioration is, in the main, due to absorption by the material of one or more of the gaseous discharge products, and regain during "rest" periods occurs owing to desorption. The gaseous absorption is initially a reversible process, but slow irreversible chemical reactions with the absorbent apparently take place, so that with a prolonged exposure the material is permanently damaged.

The fact that the increases of power factor and permittivity are closely correlated leads to the conclusion that the dielectric-loss deterioration is a macroscopic or volume effect, since if only highly localized areas were affected it is unlikely that any substantial changes in permittivity would occur.

Furthermore, it may be noted that the increase of weight per gramme of material is roughly independent of thickness in the case of black varnished cloth, and with 10-mil yellow varnished cloth the increase is three times that with 5-mil grade, which shows clearly that the processes are not confined to the surface.

In all the tests only one instance occurs of a large rise in power factor unaccompanied by a rise in permittivity or weight (sample No. 10). A result of this nature probably indicates the presence of one or more local low-resistance paths.

The results of the tests in which samples were subjected to direct and indirect corona simultaneously support the view that dielectric-loss deterioration is a consequence only of exposure to the gases present in the discharge. With yellow varnished cloth, for example (see Fig. 8), the effects of direct and indirect corona are practically the same and, although there are small differences in similar tests on black varnished cloth (see Fig. 9), they are not of great significance, taking into account that the aluminium gauge has possibly a shielding effect in some cases. The regain of properties after several weeks' rest exhibited by the samples in these tests is noteworthy and demonstrates the absence of permanent dielectric-loss deterioration due to electronic or ionic impact.

The existence of electric-strength deterioration as a distinct factor having no relation to dielectric-loss deterioration is demonstrated by the results of the direct corona tests in pure nitrogen. In this gas no dielectric-loss deterioration occurred, but some of the samples failed electrically by puncturing at the same voltages as in air. This result was not unexpected in view of the fact that in the previous tests the occurrence of breakdown was apparently unrelated to the power factor and permittivity values. Details of tests in which breakdown of sample occurred are given in Table 9.

Since dielectric-loss deterioration is a volume effect, whereas electric-strength deterioration is a surface effect, the thick samples should be capable of developing the former to a greater degree without breakdown than the thin samples. The results show that this is the case.

The dielectric-loss deterioration caused by direct corona in oxygen was only slightly less than in air, indicating that it is a consequence mainly of the action of ozone, but is accelerated somewhat by the presence of oxide of nitrogen.

The loss of weight as a consequence of exposure to direct corona in nitrogen is of some interest, as it is much greater than that shown by the control samples and must therefore be caused by the discharge. It is possible that minute solid particles may be torn from the surface of the material, which would account for the change in the surface appearance which is observed, but the loss of weight may be caused merely by the evolution of residual solvent as a result of the temperature rise.

When the results of the tests on cellulose acetate and varnished cloth which were made under the same conditions are studied (see Table 6) it is seen that whereas dielectric-loss deterioration is slower with cellulose acetate than with varnished cloth, increase of acid value and weight is greater. It is clear, therefore, that it would be inadvisable to employ only one property as a criterion to corona resistance.

Although there is as yet no definite proof, it is probable that electric-strength deterioration is associated with the action of the discharge concentrations, the existence of which is demonstrated by the photographic records. This question is now under investigation and will be considered in a future report.

(8.2) Theory of the Discharge Process

It may be useful here to consider in the light of modern theories the mechanism of the processes which occur in a stabilized discharge such as that employed in the tests. Oscillographic records and visual observation show that the corona is a discontinuous phenomenon and that a number of discharges occur between discrete points on the dielectric and the metallic electrode as the applied voltages alternate, and that the direction of the field is without influence. When the metallic electrode is negative stray electrons in the air-gap produce some ionization, which leads

* The high peak factor was a result of including a resistor in the primary circuit of the transformer for regulation.

Table 9

DETAILS OF TESTS IN WHICH BREAKDOWN OF SAMPLE OCCURRED

Material	Sample No.	Thickness of sample, cm	Thickness of air space, cm	Gas used	Details of corona exposure		
					Applied volts (r.m.s.)	Period under corona before breakdown, hours	Remarks
Cellulose acetate	4	0·013	0·089	Air	3 000	96	See Table 2
	5	0·013	0·089	Air	3 000	96	
	6	0·013	0·089	Air	3 000	327	
Black varnished cloth	4	0·013	0·19	Air	5 000	59	See Table 4 and Fig. 3
	5	0·013	0·19	Air	5 000	106	
	6	0·013	0·19	Air	5 000	123	
Yellow varnished cloth	12	0·013	0·19	Air	5 000	16	See Table 4 and Fig. 5
Yellow varnished cloth	17	0·025	0·19	O_2	5 500	8	See Figs. 10 and 11
	19	0·025	0·19	N_2	6 000	6	
	20	0·025	0·19	N_2	5 500	10	

to a positive space charge some distance from the cathode owing to the higher electronic mobility. The positive space-charge increases the transverse field and at the same time gives rise to a radial field. Electrons are therefore drawn rapidly from the neighbourhood of the cathode and adjacent regions and produce by collisions a strong wave of ionization which develops into an electronic avalanche by photo-electric action or otherwise, and this is probably the source of the spark which is observed. When this reaches the dielectric the electrons build up a charge of negative ions on the surface, since movement within the material is restricted; the discharge is then distinguished. When the metallic electrode is positive, a positive space-charge is formed nearer the dielectric and the electron avalanche proceeds towards the anode as before. The discharge will again, in general, be self-extinguishing owing to the inability of the dielectric to supply electrons necessary for its maintenance.

Thus, apart from the action of the gaseous products of the discharge, the dielectric is exposed to only a relatively weak electronic bombardment in the one case or to a high field tending to detach negative ions together with positive ion bombardment in the other case.

The question now arises as to the nature of the non-uniformity which is the origin of the discharge concentration and ultimately the source of microscopic deterioration and electrical failure. Since the discharge concentration requires some time to become observable, it is clear that the initial heterogeneity is very minute but susceptible to development. The intensity of the individual discharge certainly depends upon the supply of electrons, and at this stage three possibilities may be suggested as to the mechanism involved, namely:—

(*a*) Presence of a minute particle of impurity capable of yielding a few electrons at first, and subsequently undergoing decomposition with the production of a more abundant supply.

(*b*) Presence of a minute source as in (*a*) which causes a discharge of somewhat higher intensity than on other parts of the surface, as a result of which the adjacent material is decomposed by heating or bombardment and thereby provides a more copious source of electrons, the action being cumulative.

(*c*) Some of the electrons which possess a high velocity on colliding with the material may penetrate the surface and become trapped in a potential hollow. The positive space-charge set up near the surface on reversal of the field will attract these electrons, and under favourable circumstances the force may become sufficiently high to overcome the potential barrier, in which case the electrons will be rapidly accelerated and thereby cause ionization and decomposition of the material in their passage outwards, and thus give rise to a source of electrons.

It would be of interest to know whether puncture always occurs with the same field polarity, and it is intended to investigate this point in the tests which are now in progress.

Nevertheless, it is clear that the question of breakdown during corona is entirely distinct from any permanent deterioration caused by corona. The development of a suitable nucleus is undoubtedly a deterioration but is a microscopic effect and not normally to be detected by any macroscopic process, and it would be difficult to employ microscopic methods except those in which an actual discharge is used.

It may also be noted that the waves of ionization which give the current "kicks" in the discharge are very rapid. High-frequency components due to similar discharges in condensers, etc., have been observed up to 50 Mc/s. Thus the speed is the same as in gaseous discharges where the time of building is of the order of 10^{-7} to 10^{-8} sec and where h.f. components, as in sparking plugs, have been observed up to 150 Mc/s and possibly 300 Mc/s.

(8.3) Assessment of Corona Resistance

It has been demonstrated that it is impossible by a single test to assess the deterioration caused by the exposure of insulants to corona, since failure in a given case may be due to change in stress distribution, chemical or mechanical instability, or breakdown at a weak spot according to the conditions of use. Two tests are in general necessary, for general deterioration and for electric strength deterioration respectively.

When the material may have to withstand the attack of the gaseous products of the discharge, but not directly exposed to the discharge field, only the general deterioration requires consideration, and may be studied by exposing the material to the active gases generated separately in an ozonizer. The criterion of deterioration would be decrease in dielectric properties, increase of acidity, and/or decrease in mechanical strength according to the manner in which the insulant is to be employed.

On the other hand, when resistance to direct corona (i.e. exposure to the actual discharge field) is in question, electric-strength deterioration is, in general, of greater importance and may be investigated by exposing the material to corona in a given air gap at a given voltage with observation of the time lapse to breakdown. This test might be accelerated by a regular increase

of the voltage up to breakdown after a given period of exposure at the standard voltage, a comparison test being made without a preliminary treatment. At present it cannot be taken for granted that an accelerated test of this nature could be applied without altering the processes, and this question is now under investigation. Furthermore, although in general a plane air-gap is advantageous as a standard, yet for many purposes a cylindrical air space or a point-plane discharge may approach normal service conditions more closely and might well be permitted as a variant.

The utility of the time to breakdown method as a practical discriminatory test has in fact been demonstrated in a few tests on ignition cables, and it has been shown that some organic materials exist which definitely possess a higher degree of resistance to corona than others, at least so far as concerns the electric-strength aspect.

For quality control, a proof test, specifying a minimum time of exposure without breakdown, might be imposed, in which case appropriate tests for general deterioration could be applied to the sample afterwards if required.

(9) GENERAL CONCLUSIONS

(*a*) The effect of corona on sheet insulating materials such as cellulose acetate and varnished cloth is to cause deterioration in two ways, which are recognized as:—

(i) Dielectric-loss deterioration.
(ii) Electric-strength deterioration.

(*b*) Dielectric-loss deterioration is a volume effect, and is due entirely or mainly to absorption of the gaseous products of the discharge followed by slow chemical reactions. It may be measured by the changes in power factor and permittivity which result.

(*c*) Electric-strength deterioration is a local effect and occurs independently of dielectric-loss deterioration. It is probably caused by electronic and/or ionic bombardment, which, owing to surface irregularities or inhomogeneities, becomes concentrated on certain points, with the result that one or more nuclei are produced on the surface by decomposition. Such nuclei provide a source of electrons which enables a "main" discharge stroke or electron "avalanche" to develop from the weak ionization of the corona, and this leads to the material puncturing. So far there is no information as to whether this form of deterioration can be studied before it has developed into complete breakdown.

(*d*) Both forms of deterioration begin to be appreciable when the applied voltage is about 25% above the corona extinguishing voltage. The probability is that if the voltage is sufficiently high for corona to occur, ultimate failure of the insulation is only a question of time.

(*e*) Cellulose acetate has greater resistance to corona than varnished cloth if the electrical aspect only is considered, since the rates of both dielectric-loss and electric-strength deterioration are slower for the former than for the latter; from the standpoint of chemical deterioration, however, cellulose acetate is inferior to varnished cloth owing to the more copious production of acid capable of attacking metal.

(*f*) No single test is adequate for the determination of resistance to direct corona. At least two tests are necessary, one to show the resistance to general deterioration, the criterion being the change in property or properties selected according to the method of use, and the other to show the resistance to the microscopic form of deterioration, which is probably only detectable by exposure to a direct discharge.

(*g*) The apparatus described in Section 5.2 (Fig. 1) is satisfactory for the purpose of the study of the effect of direct corona on sheet insulating materials under controlled conditions.

(10) ACKNOWLEDGMENTS

The author is indebted to the Director of the British Electrical and Allied Industries Research Association for permission to publish this paper, and to Dr. S. Whitehead for helpful criticism and advice.

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DISCUSSION ON "BONDED DEPOSITS ON ECONOMIZER HEATING SURFACES"*

NORTH MIDLAND CENTRE, AT LEEDS, 18TH JANUARY, 1944

Mr. G. P. Henzell: Some years ago I made a number of experiments using polished steel plates exposed to the boiler exit gases on one side and water cooled on the other. A sticky deposit formed very quickly on the side exposed to the gases, giving a "fly-paper" effect as the fine grits adhered to the sticky surface, and several layers of deposit were built up. The sticky deposit was highly acid and corrosive. I tried to remove it by steam blowers without success, but it could easily be washed off by water jets.

Can the authors say whether the gilled tube is more susceptible to bonded deposits than a plain tube? I have some economizers in service with plain steel tubes and have not experienced much trouble with deposits on them. It is true that the boilers are not of modern design and that the rating is more generous than on many modern boiler installations. Have the authors been able to relate modern ratings with bonded deposits?

I am much interested in the presence of aluminium sulphate in these deposits. Have the authors reason to suspect the presence of aluminium sulphate elsewhere than in the economizer?

Yorkshire coals are generally rather higher in sulphur than the figures given by the authors, and the general experience in Yorkshire is that soot blowing alone will not effectively remove deposits from economizer tubes. The best method seems to be water washing at regular intervals, according to our experience in Yorkshire, but I understand that in other parts of the country washing has not been effective. Can the authors throw any light on this variability?

We may have a long road to travel before combustion conditions are realized which will secure us against the formation

* Paper by J. R. RYLANDS and J. R. JENKINSON (see 1944, 91, Part II, p. 77).

of deposits in all parts of the boiler, but much can be done by tackling the trouble at this end. More liberal ratings, the provision of a combustion chamber of ample size, and the more effective use of secondary air, would I think, form an effective contribution towards preventing the formation of these very troublesome deposits.

Mr. W. D. Jarvis: The authors have propounded a new hypothesis on the formation of bonded deposits on economizer and air-heater surfaces which depends upon the interaction of alumina in the fly ash particles, and sulphuric acid manufactured locally from sulphuric anhydride in the flue gases. In support of their hypothesis the authors state that alumina and sulphuric acid are present in all deposits. They show that the two substances which are active agents in producing bonded deposits are ferric and aluminium sulphates. From my own examination of many bonded deposits, it appears that not only alumina but also iron and silica are always present with sulphuric acid. These three radicals are present in a three-component system in fly ash which has passed through the furnace. I do not think that the action of sulphuric acid on such an ash constituent will be as active as is suggested in the graph. With most Yorkshire coals the amount of iron oxide in the ash is greater than that of alumina.

If the hypothesis of the action of aluminium sulphate on the formation of bonded deposits may be accepted, the root cause of the manufacture of sulphuric acid and the formation of aluminium sulphate is the amount of ferric sulphate present, and more investigation is needed on the causes which produce this substance in place of ferric oxide.

Iron and sulphur are present in coal as iron pyrites (FeS_2) which is less reactive with oxygen than coal substance; it is oxidized to ferric oxide and sulphur dioxide with difficulty. Under suitable conditions, it may provide a much greater source of ferric sulphate than by the solution of economizer metal by a thin film of sulphuric acid. Ferric sulphate is deliquescent and takes up 9 molecules of water when in contact with water vapour. On heating, in the presence of water and/or sulphuric acid, the hydrated salt behaves similarly to aluminium sulphate and finally sets as a hard bonded mass. I believe that the degree of oxidation of the iron has a considerable influence on the physical character of the deposits. It is significant, however, that a greater weight of oxygen is required to form ferric sulphate from iron pyrites than to form ferric oxide and sulphur dioxide. I have mixed a fully-oxidized sample of coal ash with an amount of sulphuric acid equivalent to that found in economizer deposits and then extracted the soluble deposits with water. Iron was not found in the aqueous solution, but alumina was present. It is probable that the fly ash in which the iron content is fully oxidized will be deposited as dust. Was the same amount of water used in each of the authors' experiments, and is the acid concentration the same in each experiment?

I suggest that to control the formation of bonded deposits a more fully oxidizing atmosphere at all times should be maintained in the combustion chamber of stoker-fired boilers.

Mr. E. Lunn: The majority of engineers in the industrial plants referred to have comparatively little trouble with their economizers, although blunt scraper gear is liable to iron-on the scale instead of scraping it off. Cold feed-water does accentuate the trouble experienced with soot blowers or scraper gear, and I have come across feed temperatures as low as 60° F in factory plants. There is, however, a wide gap between the average factory plant and generating-station conditions. Although the "dew-point" factor is allowed to be contributory in causing bonded deposits, the fact that they have been known to form when the metal surfaces were well above the gas dew-point, indicates other contributory factors.

The authors have undertaken a most difficult task, for their investigations have produced such conflicting and dissimilar data, e.g. in the Table on stations X and Y. It is interesting to find that aluminium sulphate, which forms a large part of the hard deposits, is inclined to be highly glutinous at about 420° F, which intensifies the building-up of the deposits. The starting-up of a plant with cold water through the economizer, with its resultant speeding-up of bonded deposits, is not treated as seriously as it should be by some engineers. The authors' warning against neutralizing agents in the washing water is worth noting, and as it is claimed that it is essential not to leave even 0·01in scale on any of the tubes, an effort appears to be called for to make economizers easily removable, and to install a spare, in order to reduce plant outage time and facilitate a more thorough cleaning of the unit.

The changing of economizer soot blowers to blow with the gases instead of against them has proved a marked improvement.

Mr. A. G. Connell: As regards the comparatively long duration of initial immunity after economizers are put into service, the authors will no doubt have paid careful attention to the first coat which is the beginning of the trouble. On the question of economizer washing, we must look to boiler designers to determine the positions of economizers and air heaters relative to the boilers.

Mr. H. H. Hobbs: The suggested method of preheating an economizer is unlikely to give a temperature much higher than 100° F, owing to the difference between the mass of metal and the water capacity. I suggest the use of steam injection to raise the temperature to about 200° F. The weight of steam required would be only about one third of the weight of the water capacity, and the additional water added by condensation of the steam would pass forward into the boiler section. Means to provide circulation during the preheating period would be required. It might be desirable to raise the temperature of the whole boiler unit by steam injection to prevent the deposit of tarry substances during steam raising, and to maintain a higher gas temperature at the air heater.

The maximum deposit occurs where the gas velocity is highest, and as the grit concentration in the gases passing through the economizer may be three times greater than in the early passes of a boiler, due to the smaller volume, it would appear that a reduction in the draught loss across the economizer would slow down the rate of deposit.

The authors do not consider that moisture introduced by soot blowing is of great importance, but I have found that deposits near soot blowers are more difficult to remove by hand than those more distant. I do not think that in any plant soot blowing is done throughout by superheated steam. There is always a period when the blowers are acting as drains passing free moisture.

Mr. R. H. Coates: Although the paper deals specifically with deposits on economizers, reference is made to deposits on other parts of the boiler and I would like to raise a point with regard to such deposits. In Section 1.5 the authors appear to discredit the sodium salt hypothesis. Although the hypothesis the authors propound is well supported, I think it would be a great pity if, in accepting their hypothesis, we were led to reject equally sound hypotheses. The authors refer to the small amount of sodium salts in the gases and consider that previous investigators, in giving figures for sodium sulphate in deposits, varying from 84% to 2%, indicate that their results are unreliable.

In Sheffield, we have had deposits on superheaters, which, when analysed, have given up to 95% sodium or potassium sulphate in one part and as low as 2% in other parts of the same deposit. The explanation put forward by our chemists over four years ago is, briefly, that the conditions are such that on the

clean tube a thin deposit of alkali salt forms very slowly, because there is only a limited amount available in the gases. The tube surface is relatively cold and the layer of alkali is hard and not sticky, so that no ash is held. This is the period of immunity. As the layer gets thicker, its surface temperature rises until a point is reached when it is sticky; at this point a thin layer of fine ash is held and seals up the sticky surface.

A further thin layer of alkali forms and collects another thin layer of ash, and this second period of formation produces thin alternate layers of sulphate deposit and ash, similar in appearance to Fig. 10 in the paper. Thirdly, the temperature of the deposit is sufficiently high for the sulphate to remain freely fluid, and the ash and sulphate collect simultaneously. Finally, the surface temperature is sufficiently high for some of the ash itself to be soft, and the ash will build up apparently without the need of the sulphate bond.

An analysis of the deposits gave:—

	Stages 1 and 2	Stage 3	Stage 4
	%	%	%
Alkali sulphate	60	16	2·6
Ferric sulphate	16	—	—
Silica	9	26	31
Iron oxide	—	22	31
Alumina	7	22	35

It is seen that, contrary to the authors' contention, the sodium-salt hypothesis can explain the period of immunity on surfaces where the temperature conditions render the dew-point and the authors' hypotheses totally inapplicable.

Mr. W. A. Slorick: Have the authors given any consideration to the possibility of electrostatic charges created by frictional electricity helping in the formation of the finger-like particles in the deposits?

Mr. R. M. Longman: Greater attention should be given to combustion, and I suggest that greater turbulence, as in the case of powdered-fuel burners, would be an advantage, and this in turn may remove some of the sources of trouble in superheaters, air-heaters and economizers. In general, the design of the complete boiler is too much of a collective effort, and the greatest skill and experience is necessary in co-ordinating the several items to obtain the best results.

The difficulties of generating engineers at the present time have been greatly increased by the poor and variable quality of fuels. Possibly if colliery agents were made responsible for the operation of the generating plant, the quality and uniformity of the fuel supplied would be much improved.

The apparent period of immunity evidently demands much closer attention than has previously been given it, and a thorough wash-through, preferably with a caustic solution, would increase the period of immunity.

[The authors' reply to this discussion will be found on page 567.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 7TH FEBRUARY, 1944

Mr. F. W. Lawton: War-time conditions have largely been responsible for bringing into prominence problems associated with boiler availability. The high loads which boilers are now called on to perform have resulted in both high and low temperature zones being fouled, particularly on stoker-fired boilers, as in addition to the loading conditions fuels of varying character have been supplied. The authors are right in their statement that pulverized-fuel-fired installations are relatively immune when compared with stoker-fired units, but this is true only if the pulverized-fuel-fired units are very liberally rated. On the other hand, stoker-fired units would be relatively immune from bonded deposits if, say, a burning rate not exceeding 30 lb/ft^2 of grate area could be maintained, whereas in practice rates up to 55 lb/ft^2 are common in the later types of boilers.

The authors are to be congratulated on their scientific approach to this most difficult problem, and they will no doubt agree that the chemical analyses of the deposits shown in the Table in Section 2.1 are at best speculative, as in the deposits examined the presence of free sulphuric acid, ferric sulphate, aluminium sulphate, ferric oxide, and alumina, presents some difficulty in obtaining a true combination of sulphuric acid with iron and aluminium oxides in the original deposit.

In the analysis of the soluble matter given in the paper, it is unfortunate that sodium had not been determined, since its presence would reduce the figure for free sulphuric acid, and an equivalent amount of sodium sulphate would appear in the analysis.

In pulverized-fuel-fired boilers, we have found deposits from the top bank of the tubes of the steaming economizer at the hottest part of the economizer where the outlet-water temperature is about 480° F. According to the hypothesis outlined in the paper, which appears to be sound, this temperature would favour the formation of deposits by promoting the formation of sulphuric acid on the tube surfaces.

The paper is a valuable contribution towards a more complete understanding of complex phenomena in low-temperature zones. There are equally difficult deposits being formed at high boiler ratings in high-temperature zones, notably in the superheaters. So far, water washing of the affected surfaces is the most suitable means of removing the deposits so formed, but it is extremely difficult to clean the tube surfaces thoroughly by this means.

By no means are all the problems associated with boiler availability solved, and further investigations and field experiments are now proceeding under the auspices of the Boiler Availability Committee; and it is anticipated that in due course, when all the relevant data are available, a final solution will be found. Modifications in boiler design are clearly indicated by the information so far available, such as, for example, combustion-chamber shape and the disposition of burners in pulverized-fuel-fired installations.

So far as stoker-fired units are concerned, everything to date points to the fact that grates are being too highly rated for the conditions under which they have to operate, and many expedients have already been tried, such as reducing the proportion of fines fed to these units, and introducing lime over the grate; even pulverized-fuel dust has been admitted. All these expedients, however, do not tackle the fundamental problem, and it will need much further research before a complete solution is likely to be found.

Mr. L. F. Jeffrey: This appears to be the first serious attempt to tackle the problem of bonded deposits scientifically and logically. Having accepted a theory to account for these deposits, how can they be avoided? The authors have indicated in a general way some measures which might be taken, but I suggest that more attention should be given to the treatment of coal at the source, and possibly also in the combustion chamber of the boiler itself.

The rating of boilers, and particularly stokers, must be kept down to reasonable limits. Mr. Lawton has given a figure of 55 lb/ft^2 of grate area per hour. I have a plant working at a higher rating—about 58 lb/ft^2 per hour. The responsibility for this state of affairs is not only with the boiler designers, because so often they have only a small space in which to put their plant, and it is only natural that they do their best in competition with

other makers to get the best out of that space. We must allocate more space and provide higher building costs to give the boiler designer a better chance.

Mr. Lawton also referred to the features of the boiler proper, such as the shape of the combustion chambers. I would add the first pass of the boiler, with a view to giving the superheater a better chance.

Why is it that some stoker-fired units will give a very heavy deposit on either economizers or air-heaters, whereas in others practically no trouble occurs? I recently visited a high-pressure plant in the London area where the main trouble was very heavy deposits in the air-heater passes; no satisfactory explanation of it was forthcoming. In my own experience the worst troubles have been in the superheater zone; the authors have indicated that their line of approach might be applicable to the superheater zone. I should like to have further information on their proposed investigation. I think it is fairly well accepted that the sodium-sulphate hypothesis is to some extent applicable to the superheater, for usually the initial deposit is a hard sodium-sulphate deposit which cannot be removed by soot-blowers or any other means. Another important point as regards the superheater zone is the fusion point of the ash. In this zone the degree of superheat must be maintained continuously. It is not satisfactory to start with 850° F and then at the end of 300 hours drop to 750° F. I have had boilers which after 280 hours have been completely fouled.

In my own experience water lancing has been installed with boilers of the Stirling type, and after 2 000 hours they were water-lanced off load approximately once a week without any fall in superheat. Washing on load caused the superheat temperature to drop by about 50° F. I think the deposits should be prevented and soot-blowing and water-washing regarded merely as palliatives. Further investigations should be carried out on the superheater zone, and some satisfactory explanation of these deposits and means for their reduction proposed.

Mr. F. H. S. Brown: The authors state that acid is manufactured below the surface of the scale and close to the economizer tube. If this is so, then what may be termed stage 1 of the manufacture of the scale, i.e. direct attack of alumina in the fly ash adhering to the acid-coated tube, can proceed precisely as the authors suggest. Further stages must, however, differ, since the fresh acid at the tube surface is mechanically protected from supplies of fresh alumina by the thin film of scale formed during stage 1. I therefore suggest that the acid formed after stage 1 must either attack the residual alumina still existing in the first layer of scale formed, or alternatively, being a weaker acid due to the lower temperature of the tube surface owing to the thermal insulation effect of the first layer of scale, will redissolve the precipitated aluminium sulphate, carry it in solution through the scale and reprecipitate it at the hotter gas surface of the scale. In either case, I suggest that a migration of aluminium compounds must occur away from the tube and towards the gas surface of the scale.

This suggests a possible explanation of a phenomenon observed at one of our local stations, where we have induced-draught fans with a large reserve of power. Here a clean economizer gives a pressure drop of 1 in w.g., and 3 000–4 000 hr steaming gives virtually no increase. After 4 000 hr the drop increases rapidly until at about 5 000–6 000 hr it is 4 in w.g. Normally we take out the boiler and clean at or before this point, but recently, due to the paramount importance at times of keeping the boilers on load, we have steamed for as long as another 2 000 hr or more, using an economizer with 4 in w.g. drop. The surprising fact is that once the drop through the economizer has reached 4 in, further steaming for an indefinite period causes no appreciable increase in this drop. I submit that if the migration of aluminium salts suggested above does occur, then there must come a time when equilibrium is established and no aluminium compounds remain sufficiently near the tube for further acid attacks to take place. An equilibrium of some sort is certainly established at this 4 in w.g. drop, and, failing this explanation, I should be interested to hear whether the authors have any alternative to offer.

Flue-gas temperatures are affected surprisingly little by this very thick scale. Why this is so I do not know, unless possibly the high turbulence of the gases due to the increased velocity caused by the narrowing of the gas spaces by the scale, increases the efficiency of heat transfer and thereby partially overcomes the insulation effect of the scale.

Concerning the position of the air-heater: at our station we have plate-type air-heaters placed vertically above the economizers, which has proved advantageous. Normally the air-heaters do not foul rapidly, but recently we decided to wash them and found that, as we expected, the water falling from the heater through the economizer, and so to waste, automatically washes the economizer without extra trouble.

Dr. W. G. Thompson: The paper is an example of observation and deduction applied to most complex phenomena. The authors have attacked the problem mainly from the chemical standpoint, but I should like to comment briefly on a few of the physical concepts involved. It is known that the build-up of deposit on a cylindrical surface in a smoke tunnel is dependent upon the air-flow. This air-flow is of the type shown in Fig. A. The

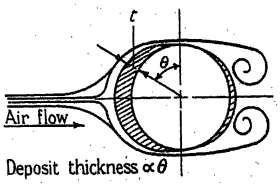


Fig. A

suspended matter is deposited with a thickness proportional to the complement of the angle of incidence, decreasing from a maximum along the axis of flow to zero at the tangential-flow position. The rate of build-up is directly proportional to the surface roughness and a constant depending upon the adhesion of the suspended particles. With hard particles the line passes through the origin as shown in Fig. B, but with softer particles

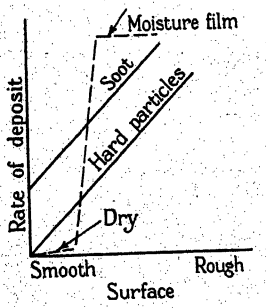


Fig. B

this line is displaced upwards. This suggests an explanation for the difference between the behaviour of hard pulverized-fuel combustion spheres and the lower temperature products from chain grates. Incidentally, the rate of deposition is increased enormously when a complete liquid film is formed on the surface. Some of the deposits shown by the authors exhibit a wave formation towards the direction of gas flow; such a phenomenon can be produced by air-flow conditions. Is this so in the present

instance, or are the reasons purely chemical? Have the authors taken any micro-sections of the bond between the deposits and the metal? These might throw further light on the process of their formation.

It is interesting that the deposits are not removed by the expansion and contraction of the surface: this seems to indicate that their scaly, granular structure results in an aggregate with an appreciable amount of elasticity. Finally, is there any evidence of shot-blasting with the pulverized-fuel particles?

[The authors' reply to this discussion will be found on page 567.]

WEST WALES SUB-CENTRE, AT SWANSEA, 19TH FEBRUARY, 1944

Mr. J. Bruce: I cannot quite follow the authors' reasoning as to why a plant should enjoy comparative immunity from deposit trouble during a period of approximately six months after being put into service. This is exceptional, for, in this initial period, numbers of shut-downs have to be accepted for making adjustments and the eradication of "teething" troubles, thus providing the frequent wide variations in temperatures which are stated to influence the rate of growth of the deposits.

The authors' theory, supported as it is by corroborative evidence, indicates that the reactions between certain constituents of the flue-gas dust and sulphuric acid account wholly for the formation of bonded deposits in the economizer. I agree that the fused-ash theory appears inapplicable at such a distance from the combustion chamber, and though plastic fused ash is the principal contributory agent in the bird nesting of the first rows of the boiler convection bank, its effect on more complicated deposits may, with low-fusion-ash coals, extend further than just the first bank of boiler tubes.

In the economizer zone, can the dew-point be entirely ignored, especially where a high sulphur trioxide content is prevalent in the flue gases, and may there not be contributory factors other than the reactions detailed in the paper?

The authors deal only with economizer deposits, but parts of the boiler heating surfaces just prior to the economizer can, at times, be operating under the conditions which they state can produce these deposits. Bonded deposits of an equally serious nature also occur in the high-temperature sections of the boiler convection-heating surfaces and in the still higher temperature zone of the superheater. To both these zones, the authors' theories cannot be applied. Does this mean that, from the combustion chamber to the gas outlet from the combined unit, fused ash, sodium sulphate, the processes described in the paper and the dew-point, all contribute within their respective temperature ranges to the formation of bonded deposits, all of different composition, throughout the complete boiler unit?

The suggestions and recommendations for minimizing the rate of production of economizer deposits, in so far as these are affected by plant operation, are not always applicable.

In a new station the first boiler unit, at least, has to be started up on cold water, and in new boiler plant that is an extension of an existing station, and in boiler filling after annual survey, etc., it is not always possible and not desirable to fill the cold unit with high-temperature water from the feed range. In any case, the weight of cold metal in a modern unit will rapidly cool the high-temperature water and thus nullify the advantage of the recommendation.

The authors' recommendations of methods for cleaning the bonded deposits on economizers are probably advanced only as a temporary measure, for I do not think this suggestion is intended as a means to a final end. The suggestions as to water washing mean that the outage to wash and ensure removal of all salts in the washing water is such that the outage from chokage by deposits and the necessary clearance by washing will involve a time period that is entirely uneconomical. Further, if water washing is the only thing left to us, I am perturbed at the authors' suggestions for radical alterations in the design of economizers and economizer housings, etc., to facilitate water washing, all of which can only result in increased costs of boiler plant operated with travelling-grate mechanical stokers.

Surely, in all the problems affecting boiler-plant outage resulting from bonded or other deposits, the cause and the remedy should be sought elsewhere than in the particular region where these deposits occur. The paper emphasizes one significant fact: pulverized-fuel plants enjoy an immunity from bonded deposits very much greater than do boiler plants with travelling-grate mechanical stokers. I think research is required to determine the differences in the constitution of the products of combustion in pulverized-fuel and chain-grate travelling stokers.

The paper mentions the effect of high contents of sulphur trioxide. I agree with the authors on this point concerning pulverized fuel, but suggest that investigation should be made as to what zone in the chain-grate installation contributes most to the production of these oxides. It appears that the rear end of the travelling-grate stoker, where only ash and a small percentage of fixed carbon exist, could be a prolific source for the generation of these oxides from the pyritic sulphur carried in the ash.

It should be pointed out that bonded deposits were known prior to the present abnormal conditions, and that they have now occurred in plants which were immune prior to the present abnormal conditions. The quality of the coal supplied to all plants has deteriorated since these abnormal conditions supervened, and, in spite of this deterioration, boiler plant operated on pulverized-fuel systems have been able to operate for long periods under fuel conditions of a very adverse nature without loss of availability. Can the authors give any information to show the effect of deterioration in coal quality on travelling-grate mechanical stokers and pulverized-fuel equipment, in so far as such deterioration affects the production of bonded deposits?

Mr. A. C. Thirtle: The tendency for larger boiler units increases the importance of boiler availability. When it is realized that the boilers and their associated auxiliaries represent approximately 45% of the total capital cost of a station, any efforts to increase the earning power of this plant, by improving its availability, are very well worth while.

The paper is a most valuable contribution towards the solution of one of the causes of low availability of boiler plant, but not too much stress should be laid on the effect of deposits on the general question of availability. This effect is referred to as one of the chief groups of availability problems; while this is correct it is certainly not the cause of the greatest number of hours lost. The data presented in the paper by Messrs. Biles and Maxfield* show the chief culprits to be stokers and refractories. I think this evidence and the present paper are strong arguments in favour of powdered-fuel firing as against stoker-fired units. We in Swansea can fully support the statement that hard bonded deposits do not occur with powdered-fuel firing.

I have had serious trouble with this problem on stoker installations and would have welcomed the benefit of the authors' research at that time. The deposits in question occurred on superheaters, economizers and, to a lesser extent, air-heaters. The troubles on economizers were dealt with by washing during annual overhauls, but this did not always avoid deposits in the

* See *Journal I.E.E.*, 1944, 91, Part II, p. 254.

periods between overhauls. My experience was that less trouble occurred with air-heaters of the Ljungström type, provided soot blowing was kept at a minimum. Have the authors any information regarding this type of air-heater?

In Section 2.5 it is stated that "no sulphuric acid can form on a surface much above 640° F." How do the authors account for the very hard bonded deposits on superheater tubes?

The experimental demonstration recorded in Section 2.8 is most convincing. I have noticed this stalagmitic formation and fully agree with the authors' hypothesis of the process of its formation. I have also found similar hard deposits on the blades of induced-draught fan runners, which were very difficult to remove by chipping. The easiest method was to remove the fan runner and stand it outside the power station near the river overnight, when the moist atmosphere softened the deposit, which could easily be washed off with a water jet next morning. Can the authors explain this hard deposit on fan blades, where the theory of a cooled surface does not apply?

I agree with the authors' recommendations regarding the lay-out of plant where this trouble is likely to exist. In many cases, however, the limits of existing boiler space may prevent satisfactory arrangement of economizers and air-heaters, and plant can only be got into the available space by superimposing the air-heater on the economizer. I think all these difficulties strongly indicate that pulverized-fuel firing should be seriously considered as an alternative.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. **J. R. Rylands** and **J. R. Jenkinson** (*in reply*): We shall reply to the discussions in the chronological order of the meetings.

Leeds.

Mr. Henzell's experiments probably reproduced what we look upon as the low-temperature range of conditions. If his steel plates were cooled below the moisture dew-point he would certainly get a "fly-paper" effect. This condition sometimes occurs in industrial economizers where the entering feed-water has too low a temperature, and corresponds to the range mentioned in Section 2.8 (*a*).

We do not consider that the plain steel tube, by virtue of its relatively smooth surface, has any advantage over the gilled type in respect of deposit formation. The temperature of the metal surface is a much more important factor. Boiler rating may influence deposit formation indirectly, since (*a*) high ratings are nowadays associated with high inlet feed temperatures, and (*b*) the combustion processes may influence the condition of the alumina particles. More research is needed on this aspect.

We have had the same experience as Mr. Jarvis with washing away deposits resulting from Yorkshire coals. Recent investigations suggest that not only iron, but also phosphorus, compounds may influence the nature of the bonded deposits; the iron sulphate may, in part, have been formed from the iron in the coal ash.

In our investigation of the soluble proportions of bonded deposits, a standard water quantity was used, but the resulting acid concentration varied with the nature of the deposit. Recent experience shows that power-station economizers can be thoroughly cleaned *in situ*, and it is hardly necessary to consider going to the extreme suggested by Mr. Lunn, namely of installing a spare economizer. With our method of "pre-deposit" washing, results show that cleaning is a very rapid process.

We agree with Mr. Connell in emphasizing the need for early removal of the initial deposit film, and for providing the proper facilities in the design stage. Mr. Hobbs makes a good point in regard to preheating the various surfaces in the boiler plant prior to starting up; the use of steam for this purpose would be economical. It is true that after a time soot-blowers often leak and pass moisture into the gas stream. We have met cases where the rest of the economizer was clean, but the portion immediately under the blower nozzles was covered with a hard mass of deposit.

Mr. Coates points out that the "sodium salt" theory may well contribute to the explanation of deposit formation on superheaters; we agree, but we do not consider sodium salts to be essential for the formation of bonded deposits on economizers. The deposition of fused alkali and ash particles by a process such as described by Mr. Coates may be the explanation of the observed "layer" formation, but since the constituents arrive at the surface simultaneously, the selective character of the process is difficult to explain satisfactorily. Yet a thin layer of alkali salt is often found at the base of a deposit on a high-temperature surface. It may be that in any event the alkali salts do not adhere to the surfaces until the latter have been attacked by sulphur trioxide; the analysis given by Mr. Coates suggests that there is an initial film of iron sulphate which would, if present, agree with our explanation of the immunity period.

Up to the present time, no test on the lines of Mr. Slorick's suggestion has been practicable.

Greater turbulence in the combustion chamber, as suggested by Mr. Longman, may have pronounced advantages from the combustion standpoint, but we doubt whether it would have much influence in preventing bonded deposit formation. There is much evidence to show that coal quality influences steam plant availability, and there is much scope for investigation in this direction.

Birmingham.

Mr. Lawton suggests a definite association between bonded deposits and firing rates; we have referred to this point above. It is interesting to learn that deposits were found with pulverized-fuel-firing on steaming economizer tubes, and we consider that Mr. Lawton's explanation is sound. For the Table in Section 2.1, we estimated the alkalis in both deposits, but the quantities found were very small.

In general we agree with Mr. Jeffrey's remarks and confirm that further investigations from the standpoint of fuel characteristics are likely to lead to valuable results. It is not yet possible to account fully for the fact that deposits form in some plants but not in others. Partial answers would include such factors as feed water temperature, SO_3 content, nature of combustion process, and character of fuel.

Mr. Brown's statement of an important part of the deposit-formation process is clear and precise. There is no doubt that many chemical and even physical changes take place in the deposit itself; the equilibrium condition at any point will depend, *inter alia*, on temperature variation resulting from gas turbulence and the insulating effect of further deposit. One effect will undoubtedly be the migration of aluminium salts controlled by the temperatures at which the various reactions cease (see Figs. 4 and 5). Some such explanation would probably account for the effects observed in the station to which Mr. Brown refers.

Dr. Thompson rightly draws attention to physical influences in deposit-building, and there is little doubt that physical considerations play a part. In a hard bonded deposit, however, it

is the chemical reactions which are important. A deposit with a ripple or even a finger-like formation can be produced by air-flow conditions, but a hard bonded deposit indicates chemical changes.

We have had difficulty in securing samples of metal tube with the deposit adhering undisturbed. Examination of the outer surfaces of tubes and the inner surfaces of deposits does, however, indicate that the process commences with chemical action between the gases and the metal.

We have found no evidence that there is any marked shot-blasting effect with pulverized-fuel particles, which are smooth and round, and impinge on the surfaces with a relatively low velocity.

Swansea.

Mr. Bruce draws attention to the additional severity of conditions where "teething" troubles occur on new plant. We would point out, however, that where cast-iron or cast-iron protected economizers are used, the siliceous skin on all sand-cast products provides an additional resistance to acid attack. The value of this "casting skin" is particularly apparent in new plant, and helps to preserve the immunity period during the "teething troubles."

Mr. Bruce rightly points out that our theories in respect of bonded deposits in economizers do not apply to deposits in, for example, the high-temperature zones of the superheater. Each temperature range has its characteristic deposits; our investigations have been restricted to the economizer temperature range, but we suggest that our method of approach may produce useful results when applied to other temperature ranges.

One fact which has emerged from investigations into the combustion processes of stoker-fired plant is that conditions at the dumping end of the grate are important in regard to both SO_3 and fly-ash formation. The influence of coal quality is debatable, and much work remains to be done. Some fuels give trouble, others do not; some blends are good, others lead to deposit formation.

The deposits on fan impeller blades belong to the "dew-point" region (see Fig. 12), in which the bond is probably iron sulphate, and its deliquescent nature explains the ease with which the "weathered" deposit could be removed by washing.

Air-heater deposits belong, as a general rule, to the low-temperature, moisture-dewpoint region. The problem here is to maintain the metal at a temperature sufficiently high to prevent moisture deposition; various devices are adopted to achieve this end. Superheater deposits, on the other hand, belong to a temperature range outside the scope of our present investigations. Theories based on fused ash and alkali salts may account for such deposits; it is not unlikely that internal changes may also play a part.

DISCUSSION ON "INSTRUMENT TRANSFORMERS"*

NORTH-EASTERN CENTRE, AT NEWCASTLE, 13TH MARCH, 1944

Mr. E. Fawssett: I attended the discussion on this paper in London, when much of the argument centred on how the method really works; does the flux in the main core vanish when compensation is perfect, and, if so, could not the iron be removed? I believe that such a transformer would prove in practice to be a very bad one indeed, and that the iron is necessary. I understand there are several contradictory explanations of what goes on, and I should be grateful if the author could now sift them and give a considered answer.

We are specially interested in bushing transformers of very low ampere-turns, say 50 or less, which would be very bad indeed if uncorrected. Would the author indicate the general design for a compensated bushing transformer for, say, 30-ampere-turns full load, with an internal diameter of 6 in to operate a meter taking, with leads, 2 VA burden, and to give a straight line accuracy down to at least one-tenth full load. From his table I get the impression that such a transformer, if possible at all, would have an enormous quantity of iron in it and perhaps be quite uneconomic.

Mr. R. W. Wild: I conclude from the paper that the author is familiar with Brook's patent taken out in 1920, as the methods of compensation appear to me to be very similar, the only apparent difference being that Brook combines principal and auxiliary secondary windings to effect the desired compensation, whereas the author operates the corresponding windings separately. As the author states, various methods of compensation for current transformers have been tried for many years, but general commercial practice has shown very little inclination to adopt any of the various schemes developed. It might, consequently, be asked why these compensated transformers have only met a general indifference. I agree with the author that the most favourable commercial application seems to be to the high-voltage bushing transformer, where, owing to the primary current being relatively low, the scope for accuracy is very cramped. But even this application also is very limited in practice, because of the demand for VA outputs beyond the range of bar primaries. I think the reasons why compensated current transformers have not had a more favourable reception are that: (1) they are more costly and take up more room; (2) the improvement in magnetic materials and their application has enabled the requisite accuracies to be met for the great majority of commercial requirements, and (3) the VA burdens demanded to-day usually take the transformer design into the range and class where the required accuracies can be attained with few practical difficulties. Moreover, the advantages of spirally-wound cores of particular grades of material, for example, are appreciable, quite apart from the resulting economy in material and labour; and, when the attainable transformer accuracies are related to the permissible limits of error for commercial electricity meters, it will be generally agreed that commercial current transformers leave very little to be desired from the point of view of accuracy.

Mr. J. C. Wilson: I think the author is to be congratulated on having thought out such a simple scheme for adapting the Arnold current-transformer testing outfit for use with voltage

* Paper by A. Hobson (see 1944, 91, Part II, p. 147).

transformers. When the h.v. and heavy-current circuits are adjacent, it will be worth while to use this method. Since the h.v. circuits are often in another part of the building, there is no advantage in having a combination outfit.

I should like to ask how the author's method compares with the bridge. I have had experience with this method, using capacitance in parallel with resistance to measure the phase angle, employing standard transformers as a reference. Each standard can be used for several ratios, and two or three will cover the range from 22 kV downwards. So far as I can see, the author's method will require a standard of the same nominal ratio as the transformer under test. I know of at least twelve different ratios in use in this district, and the cost of that number of standards, including N.P.L. certificates, would be very great.

The absolute method of testing with a high-voltage resistor is mentioned. When testing a 3-phase transformer with this method it will be necessary to earth one phase, if phase-to-phase tests are required. Will this overstress the insulation? Will it cause any change in the phase angle or danger to supply transformers? I should also point out that the supply transformers should have sufficient kVA capacity, so that no unbalance of voltage occurs when resistors or standard transformers are put across phases. Does any drift occur in the ratio and phase angle of a standard resistor or transformer over a long period of years?

In making tests it is quite usual for the white phase of the secondary to be earthed, and in testing red-white and blue-white the galvanometer can be near earth potential. Is any trouble experienced with a residual galvanometer deflection when testing the red-blue phase?

We are indebted to the author for his clear exposition of the M. & G. diagram. I have always had a doubt about calculated values for different burdens, and still feel that, even with the simplified method, if an actual test is possible it is better to make it. The watt-hour meter is generally available, and the instrument burden can easily be simulated. The author mentions the extremely good agreement between his calculated figures and the test results. It may have been so in this particular instance, but would such good agreement have been obtained in every case if the method had been applied to a dozen different types of transformer?

In power stations, switchgear is often some distance from the operating board, and the resistance of the leads must then be taken into account. There may also be a regulator burden of 200–300 VA across two of the phases; although it is usually on a separate winding, this may slightly affect the accuracy of the other circuit. Under conditions such as these, I think that nothing can replace an actual test under working conditions.

Mr. R. Eggleton: The test results of the compensated transformer described are most encouraging. Test figures are given for a compensated transformer with 500 ampere-turns. I suggest that this is unnecessary as no difficulty will be experienced in meeting all B.S. 81 classes with a transformer of this type. If difficulty is experienced at all, this will be at 150 ampere-turns and below; even so, if engineers would specify transformers having low outputs, instead of transformers with outputs far in excess of the connected burden, much of the difficulty could be avoided. Where units are at some distance from the transformers, it will probably be necessary to supply 1- or even ½-ampere secondaries with part-turn compensation.

I have been responsible for the design of a number of transformers, but have never found it necessary to supply one of the compensated type. It would be helpful if the author would indicate the vector diagram for his compensated transformer.

Is it true that, owing to variations in the compensating cores, the compensating burden will vary for different transformers, bearing in mind that Mumetal cores vary with the tightness with which the core is wound?

I take it that a transformer having an output of, say, 5 VA would be compensated for, say, 2½ VA in order to obtain the best results over the range. For thermal reasons, the compensating burden would probably have to be mounted remote from the transformers where more than one set of transformers is required, and steps taken to ensure that this burden is not inadvertently disconnected, otherwise large errors would appear in the main secondary winding.

More often than not, protective transformers are supplied at the same time as metering transformers; this automatically provides the necessary ampere-turns for low-ratio transformers, as wound types are usually supplied. The protective transformer requires a high saturation value and the normal error is of little importance.

I think that the necessity of bar-type transformers has been over-emphasized for h.v. switchgear, for with recent developments, such as gas-blast and small oil volume, wound-type transformers are now supplied up to and including 132 kV. I consider it preferable to supply orthodox transformers, even though the transformer is more expensive, since the added complications of the compensated type do not appear to justify the advantages gained.

Dr. R. Willheim: The author's ingenious arrangement of a compensated current transformer would work in practically the same way if the tertiary winding were dropped and the impedance Z transferred to the main secondary circuit (Fig. A). The

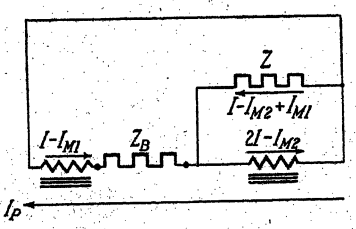


Fig. A.—Hobson's equivalent circuit.

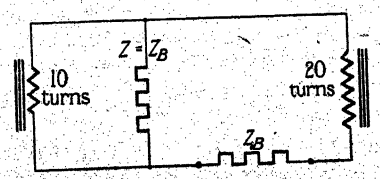


Fig. B.—Wellings and Mayo: British Patent No. 286431, Fig. 5 of provisional specification.

(I) Voltage across burden Z_B: $(I-I_{M1})Z_B$
(II) Voltage across auxiliary impedance Z: $(I-I_{M2}+I_{M1})Z$
(III) Voltage required from main core: $I(Z_B-Z)+I_{M2}Z-I_{M1}(Z_B+Z)$

arrangement in Fig. B is, according to the description given by its inventors Wellings and Mayo, essentially the same, even in such details as core sizes, nominal ratios of the two transformers, and dimensioning of the auxiliary burden.

I should like to enlarge on the explanation offered by the present author. The expressions (I) and (II) under Figs. A and B give the voltages across the burden and the auxiliary impedance. Their difference (III) determines the balancing e.m.f. required from the main core. If the burden varies, the errors are, according to the first term in (III), the same as those of an uncompensated current transformer of half the total core volume, working on the burden difference $Z_B - Z$. Particularly in multi-turn transformers with their larger secondary leakage reactance, the inconstancy of this term produces a "decompensation." Thus the main core performs a definite function when $Z \neq Z_B$.

The second term in (III) shows the effect of the magnetizing current of the auxiliary core. Both influences are reduced by pre-magnetization. The author prefers pre-magnetization through a potential transformer, but the source of pre-magnetization should rather be in phase with the current.

In Section 3, the author suggests special tests to furnish data for his second method for calculating errors of three-phase voltage transformers. Actually all these data can easily be derived from the usual phase-to-neutral tests. For zero burden the phase-to-phase errors can be calculated from the author's formulae (1) and (2) in Section 3.1. The additional errors caused by the rated burden across one leg determine Table 8 as follows: Line 2 is obtained from line 1 by adding two-thirds of the error changes, and lines 3 and 4, respectively, are obtained from line 1 by adding one-third of the error changes, with the reference system turned through plus or minus 60°, respectively.

This may be seen by replacing the original star transformer by an equivalent delta-connected transformer, giving the same additional errors on phase-to-phase loads as the original transformer on phase-to-neutral loads. In a single-phase test the adjacent delta leg evidently takes two-thirds of the current; generally, each of the equivalent transformers carries two-thirds of its own phase-to-phase load minus one-third of each of the two other loads. Moreover, this argument defines three equivalent loads which, incidentally, become identical to the original burdens, if the three external load currents form a closed triangle. Consequently, the following alternative method suggests itself: (1) Find the equivalent load from the two-thirds minus one-third combination, and (2) apply the ordinary single-phase transformer calculation method, using the phase-to-neutral error changes. The result gives immediately the error changes in terms of the phase-to-phase voltages.

Mr. D. Riach: Having regard to possible applications of the compensated current transformer in protective gear, I should like to ask the author how the compensator affects the current-transformer characteristics for over-currents of 5 to 10 times normal.

Mr. W. Gray: Considering compensating transformers as a class, the author's transformer should strictly be known as a fixed-compensation transformer. The compensation is fixed for one burden, and he has pointed out that the transformer is only accurate at the burden at which it is compensated. At any other burden the main core has to supply the difference between the burden p.d. and e.m.f. in the compensator core. Obviously, then, if the burden is made small the main core must supply quite a large amount of negative voltage. Thus, from Table 2 in Section 1.8, the transformer is compensated for a burden of 25 VA. If the transformer is loaded to only 5 VA, the main core must supply the difference, i.e. 20 VA, which will give very large errors.

Frequently in practice, a rough estimate only of the probable burden on the current transformer can be obtained, mainly because of the practice in modern power stations of installing switchgear up to 200 yd away from the control panels. This gives the current-transformer designer very little latitude and he has to supply uncompensated transformers with acceptable errors over a wide range up to the rated burden.

A further factor which discourages the use of fixed-compensation current transformers is the practice of some customers, notably the C.E.B., of insisting on having a certificate of performance at 5 VA as well as the rated burden. If the rated burden is high, e.g. 40 VA, fixed-compensation current transformers offer no advantages.

Mr. W. T. Maccall: The following appears to me to be the answer to Mr. Fawssett's question whether it is necessary to have iron in the main transformer. With a perfect compensator the main transformer would not need any iron, because the error is the product of the two errors. But there is perfect compensation at one particular load only, and when the load changes, however little, the error in the main transformer comes in, and so it must have some iron in it. As the flux density in the main transformer under normal conditions is very low, would it be better to use less iron in the main transformer and more iron in the compensator for a better overall result? If there is a certain amount of iron available, should it be divided equally? Or would it be better to put less in the main transformer and more in the compensator? In the bushing transformer this is done. With the compensator outside the main transformer there is more iron in the compensator, for although the sections are equal the diameter of the former is greater.

In Section 5.2 the author states: "Examination of the performance curves of Stalloy and Mumetal, plotted on a logarithmic basis, gave the following approximate laws for flux densities up to about 4 000 gauss sinusoidal 50-c/s magnetization . . .", these laws being symbolized by expressions (3) and (4). It seems to me that these expressions can give only average values, because at high m.m.f.'s the way the value of B varies with m.m.f. will be very different from that at very low m.m.f.'s. At very low values B will vary less rapidly than the m.m.f., which is quite different from the way it varies at 4 000; and so the rules given can only be average values. Although I do not think this invalidates the general conclusions, it would be dangerous to use such expressions as giving anything more than rough approximations. If the expressions were exact, the best ratio of length to diameter for either Stalloy or Mumetal could be calculated, but I doubt whether such a calculation is sufficiently accurate to determine the best proportion. For the actual design something much more accurate is required. Does the author think these expressions can be used for determining the best proportion of length to diameter?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. A. Hobson (*in reply*): Mr. Maccall has given an excellent answer to Mr. Fawssett's first question. In reply to his second question, it may be stated that a 30/5 amp compensated bushing transformer is quite feasible; it should be much cheaper than a wound primary transformer for 33 kV, which I assume to be the line voltage.

In reply to Mr. Wild, my compensator is clearly different in principle from that of Brook and Holtz. In my opinion previous methods have not completely succeeded, because (*a*) the improvement obtained did not justify the extra expense and bulk, and (*b*) the compensating impedances had no simple relation to the burden, thus necessitating critical adjustment of each transformer on test. The present method gives a big improvement for the same total weight of iron.

Regarding high burdens, a bushing transformer is often required to supply about 2 VA for watt-hour meters, and 13 VA for relay operation. It is then wasteful to have a 15-VA high-accuracy transformer; a far better plan is to have a low-VA compensated transformer for the meters, and a separate low-accuracy transformer for the relays. Such an arrangement gives better metering performance, is generally cheaper, and occupies no more total space.

I do not know to which bridge Mr. Wilson refers, but the adapted Arnold method probably has the advantages of simplicity and speed of operation, and also of direct reading of the error. A single standard transformer could be constructed having any number of ratios; this would result in a big saving in space, in the cost of the transformer, and in that of N.P.L.

certificates. The errors of standard voltage transformers are very stable. The insulation of a 3-phase voltage transformer having an insulated h.v. neutral will not be over-stressed if one line is earthed during testing.

The M. & G. diagram gives accurate results with all normal transformers, whether the burdens are large or small. I have carried out numerous checks.

In reply to Mr. Eggleton, the variations in compensating burden for a number of similar transformers are negligible. I see no point in mounting the compensating burden remote from the transformer, since the watt loss is very small.

Wound-type transformers for 132 kV are extremely bulky and expensive, and their complete safety is not yet fully proved. Surely bar-type transformers are much to be preferred, if they are available. The compensating method outlined in the paper offers hardly any complication.

I am interested in Dr. Willheim's remarks. Table 8 may clearly be deduced from phase-neutral results, although I doubt whether his suggested method is as simple in practice as the one in the paper.

In reply to Mr. Riach, compensation would have no great effect on the performance at five to ten times the normal current. The primary and secondary currents would be proportional to each other until both cores became saturated.

I do not agree with Mr. Gray that my apparatus is a "fixed-compensation" transformer, because the compensation may be varied to suit the burden. In fact, our usual practice is to leave the compensating winding connected to the terminals, so that the user may compensate how he pleases. No great accuracy is generally required in computing the burden.

In reply to Mr. Maccall, the expressions (3) and (4) are fairly accurate, and with suitable constants could be used for design work. I think they could be used for working out the best ratio of length to diameter, although practical conditions would usually prevent this ratio from being used.

DISCUSSION ON "THE VENTILATION OF SUBSTATIONS"*

EAST MIDLAND SUB-CENTRE, AT NOTTINGHAM, 23RD FEBRUARY, 1944

Mr. W. A. A. Burgess: We, as engineers with an eye to true economy, are always inclined to cram a quart into a pint pot, hence the compact design of switchgear and all appliances. But in due course, we find we have to provide room for maintenance purposes to enable plant and equipment to be overhauled at short notice, while to meet A.R.P. requirements, heavier buildings have to be constructed, resulting in unavoidable internal sweating. To heat a building is not enough to remedy this, for I agree that heating the air inside the building will raise the moisture-holding capacity of the air. I agree with the authors in their advocacy of ventilation, and am surprised to hear that the cost is so low.

Recently I learnt some of the difficulties of ventilation and moisture deposition encountered on various jobs. In some instances of outdoor switchgear, dry conditions existed for a time; then heaters were put in to warm the cabinets and cubicles, and mildew was found to form on the brazing. Now the subject of air circulation versus heating is being discussed. Apart from temperature, mildew can also form on the covering of v.i.r. cable. Also in air-blast switchgear and switchgear operated by air pressure, careful attention has to be given to the humidity question. Normally, the air is compressed to half or a third of its volume, and half the moisture is removed by cooling. Dryers will reduce the moisture to 10% if the temperature is controlled.

Mr. R. G. Payne: Many years ago some heaters were installed in a laundry drying room to secure a certain output of laundered articles for a given heat, but the results were disappointing. Extractor fans were then installed in different parts of the room, and the output of the laundered articles was increased by 60%. This seems to bear out the statements made by the authors.

On one of the curves I noticed that the dew-point rose above the heat of the plant. If this does not vary with the outside atmosphere, the curve cannot be accepted as exact and constant.

Mr. D. Kingsbury: I do not understand the authors' approach to the question of explosive mixtures. If something is about to fail on the switchgear, I do not think any system of ventilation could cope with an increase in the volume of dangerous gases. The oil vapour which escapes from switchgear can surely be expelled to the open air. I have noticed that some transformers for outdoor service have given trouble after blast walls were built round them, for A.R.P. reasons, as they cut off a certain amount of natural ventilation.

Mr. A. Brookes: The problem the authors have discussed and tackled is common to any electrical equipment of a similar type. Some of the troubles outlined have been experienced in telephone exchanges, although most new buildings are specially designed against sweating. In one exchange a cable with 23-gauge wire was found to have corroded right through; some impurity in the cable itself coupled with moisture deposition promoting corrosion. With pure materials, no such trouble is met. The method of temperature control in some of these exchanges does not seem right and it is very difficult to get reliable humidity control. Many of the authors' results can be applied to these buildings.

Mr. J. H. Davis: What type of trouble was found by the authors in cables in this substation, and what type of cable was affected? In investigating the effects of humidity in rural telephone exchanges in which heating is by tubular heaters switched on at 70% humidity by a humidistat, I have found slight trouble in cables, but these were lead-wrapped or braided cables, not steel-armoured. Separate cotton-lapped wires have been more affected.

With regard to Fig. 8 showing the number of days per year on which humidity reaches a given figure, it is not clear what factors have been taken into consideration in producing this curve. It will probably mean little, because judging from the power consumption at some exchanges in which heating is controlled purely by humidity, variations between corresponding quarters are extreme. I should like further information as to the basis on which the curve was drawn.

Mr. B. Nuttall: My experience has been that explosion usually precedes a fire. Have the authors had any experience of the CO_2 installation?

From the design of the substation shown, it appears that the

* Paper by F. Favell and E. W. Connon (see 1943, 90, Part II, p. 327).

windows would form a kind of chimney. It is important to stress the need for dryness and especially for a careful survey of the ground before putting up a substation. The flood level or standing-water level must be determined and the foundations designed accordingly: sometimes these latter cost more than the actual building.

Are any special precautions taken in connection with the concrete roof? Is this simply placed on top and any system of ventilation immediately underneath it? A fair amount of ventilation just beneath the roof is necessary. Where Bakelite insulation is used, it is most important to keep the air fairly dry, because of surface leakage. On one particular job the moisture penetrated the paper lamina and caused blistering.

I have been connected with the construction of buildings of a size comparable to that described, to house a rotary plant causing a fair amount of air movement; both switchgear and plant have remained in a very healthy condition. Trouble from dampness was cured by increasing the natural ventilation and obtaining correct control of the dielectric stress on open-type current transformers. I realize that movement of air assists in drying, but I do not believe in the excessive influx of air from the outside. Every substation has to be considered on its own merits. Where some coal gas is present, the less air entering the better.

I confirm the authors' experience regarding the installation of heaters in pedestals. Pedestals usually have screens on the front and are airtight; unless a system as described is adopted, trouble will be met.

Regarding acid and oil troubles, my experience is that movement of air helps to slow down the rate of acidity increase and practically no trouble will be met if air is kept from contact with the oil.

Mr. F. R. Gilks: Acidity troubles appear to be just as bad with outdoor transformers as with indoor ones, and the heating of the transformer seems to have very little effect on these difficulties. Would the authors enlarge on this point?

Mr. A. Latham: I remain unconverted regarding transformers outside substations. I recall instances where transformers have had to be taken out of substations on account of additional gear being installed, and trouble has afterwards been experienced due to mildew and general dampness, necessitating the installation of some form of heating. I assume the impeller mounted in the substation door draws air from the outside; under recent weather conditions this does not appear to be very desirable.

Mr. W. F. Perkins: Are the consumption figures in Section 6.1 actual records or do they represent estimated figures? There are several substations in Nottingham with thermostatically-controlled tubular heaters with an annual consumption of approximately 10 000 units, which seems out of proportion to the units indicated in the paper.

Mr. R. A. Nurse: Several references have been made to mildew on braided cable. Would the authors say where this cable is used in the h.v. substation and whether p.v.c. cable would avoid this trouble?

Mr. A. Pittman: I was interested in the references to telephone exchanges; although connected at various times with the installation of ventilation plant I cannot recall any instance where heat was introduced. The main considerations were always air movement and cleanliness. On what basis was the air volume of 2 000 ft^3 chosen? I understand that there are two fan sets in the building, one for circulation and one for injection of air. In all probability, the recirculating-fan equipment could be arranged with a permanent fresh-air inlet, thereby reducing the two working parts to one as well as facilitating such maintenance and inspection as is necessary. Is the heater fitted with enclosed-type or open-type elements? If the latter, what are the risks of fire? Have any interlocking devices been included in the switchgear, to safeguard against failure of the heater in the event of the fan failing?

Mr. F. Findley: In bringing air into the station, is it passed through a filter to prevent the ingress of dirt?

Mr. M. Wadeson: As most speakers have recognized, the authors approached this problem from the angle of scientific research, and to my mind they have reached very definite conclusions. They point out that the first essential for preventing moisture deposition is circulation of air and that heating is only a subsidiary means for dealing with those abnormal and infrequent atmospheric conditions which, in the absence of heating, would tend to cause deposition. Whether this is done by fans or heaters, appears to be a question rather of the size of the substation. I think that, in future, many supply authorities will find that with the large increases anticipated post-war, larger substations will be necessary, hence these problems will arise for more undertakings than at present.

It will be realized that the application of a certain amount of heat increases the growth of mildew.

With regard to explosive gases, there are several instances recorded in recent Electrical Factory Inspectors' reports which prove conclusively that explosions have taken place in substations which have not damaged individual gear but have blown the substations to pieces, resulting in fatal accidents due to the collapse of the walls.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. F. Favell and E. W. Connon (*in reply*): Mr. Burgess mentions the compression method used for drying the air for air-blast circuit-breakers. The capital cost of this method appears to rule it out for ordinary building ventilation, but it might be applied, for instance, to the mechanism and terminal boxes associated with outdoor air-blast circuit-breakers.

Mr. Payne presumably refers to Fig. 4, which is a calculated curve to show the effect, inside a building, of changes outside.

As Mr. Kingsbury points out, ventilation cannot cope with the explosive failure of switchgear. Cases have arisen, however, as mentioned by Mr. Wadeson, where buildings have collapsed without serious switchgear failure; this is probably due to a gradual accumulation of explosive gases, possibly from incipient failure under oil, and it is this accumulation which can be prevented by ventilation.

Replying to Mr. Davis, the curve showing the proportion of days on which a given humidity was exceeded at 1 p.m. B.S.T., was obtained from measurements taken under the conditions described in Section 5.3, the humidistat being set to 90% relative humidity. We would refer Mr. Gilks to references 14 and 15 of the paper and Mr. Perkins to the footnotes to Table 6.1.

As Mr. Nurse suggests, p.v.c. cable could be used in place of braided v.i.r. for control wiring, and would be less susceptible to mildew.

In reply to Messrs. Pittman and Findley, the air circulation quantity was chosen to give a sufficient air speed through the important parts of the gear. We agree that the two fans could have been combined; the arrangement described was adopted for experimental purposes. The heater has enclosed elements and is provided with a safety thermostat. Air filters are used both on the injection and circulation fans in the main installation described, but these may be dispensed with in the smaller rural substations.

DISCUSSION ON

"STANDARDS OF PERFORMANCE OF GENERATING PLANT, BASED ON FIVE YEARS' OPERATING DATA"*

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 1ST MAY, 1944

Mr. W. S. Burge: A study of the paper illustrates the many difficulties arising in any attempt to generalize on the performance of generating stations. I would like to touch briefly on two aspects of this subject.

First, it must be realized that very few generating stations have any degree of uniformity in the make-up of their total capacity, because the diversities between the several generating units in any particular station are generally greater than the diversities between stations; for instance, in the Central England district only two out of 22 generating stations have any degree of uniformity among the generating units internal to the station. In all the rest, the individual generating units vary over the widest possible range in respect of age, design features, maintenance costs, and, to a lesser extent, in respect of steam conditions. To draw dependable conclusions from these conditions, each separate generating unit must be treated as a separate generating station, but unfortunately our present method of costing analyses does not permit this.

Under present conditions with the component generating units of any station coupled together, it would be difficult to make separate cost analyses for each of the components, and the authors have done the best they could with the present method of analysis. But with Grid operation and an ever-widening difference between the total interconnected capacity of the country and the capacity of the individual generating units, there is now little need to interconnect the individual units, except on the electrical side. The reason for this is that the inertia of the national system is now so great that the sudden loss of even the largest generating unit cannot affect the frequency of the system, and so plant extensions of the future may take the form of individual generating units that are completely isolated except on the electrical side; this will greatly facilitate a better analysis and understanding of operating performance.

The second difficulty illustrated in the paper relates to our practice of expressing the thermal efficiency of power stations without any background analysis. I do not criticize our present practice of expressing the overall monthly or annual efficiencies of power stations, but to make these values intelligible it is also necessary to give in a particular form the efficiency analysis of each generating unit. The thermal efficiency of all generating units can be arrived at by the multiplication of three components: two constants and one variable. The constants are the steam-cycle efficiency and the maximum plant-item efficiencies, and the variable is the operating efficiency. Of these three components, the first is governed by physical laws, the second by the designers of the plant items concerned, and the third by the loading on the plant and the skill of the operators. Thus, an overall efficiency of 25·7% could be better expressed by $42{\cdot}7 \times 0{\cdot}64 \times 0{\cdot}94$, but this method of expression could only be applied to individual generating units with their complement of boilers and auxiliaries.

Mr. A. L. Berridge: The authors are to be congratulated on their courage and ingenuity in undertaking the very difficult task of comparing the performance of different power stations. Operating engineers have long been dissatisfied with thermal efficiency as a basis for comparing power-station performance, and, although several alternatives have been suggested, none has seemed to merit universal adoption.

Whatever method is used to determine the overall performance of power stations, it is essential that each station should adopt standard formulae and standard methods of test to arrive at the results required. It is generally agreed that the most difficult item to determine with accuracy is the heat input to the plant, and unless standard methods are used in sampling and testing fuel very considerable errors may be introduced. The methods of measuring heat input should be reduced to a common basis, and it would be interesting to know whether this was done in the group of stations referred to in the paper.

Most engineers will welcome the authors' suggestion that "operating efficiency" should be brought into station records, but many will disagree with the authors' method of assessing this item. The method set out in Section 7.7 of obtaining the efficiency ratio and hence the maximum probable efficiency is unsatisfactory in that it may result in "operating efficiency" being debited with losses which should properly be termed design losses.

There are many instances of power stations in which insufficient pressure drop between boiler blow of pressure and turbine stop-valve pressure has been allowed for, and where turbines have been designed for a vacuum which is unattainable owing to prevailing circulating-water temperatures, or where unsuitable materials have limited the steam temperature to a figure below that for which the turbines were designed. It is obvious that where such limitations exist they should not affect operating efficiency, and I therefore suggest that instead of maximum probable efficiency, as determined in the paper, the authors should consider the advisability of using a factor which might be termed "operating cycle efficiency" and which would be based on attainable stop-valve steam conditions and circulating-water inlet temperature, or alternatively a figure arrived at by test.

Some years ago Mr. C. W. Priest suggested a similar factor and pointed out that the ratio of the "ideal cycle efficiency" to the "operating cycle efficiency" might be accepted as a "design efficiency ratio."

Mr. D. P. Sayers: We cannot challenge the main conclusions set out in the paper, and I endorse particularly the suggestion that the systematic recording and open discussion of failures would benefit the whole industry. Station engineers generally have been reluctant to talk about failures in the past, and it would be beneficial if particulars of all failures could be collected and collated by some central body and circulated to all engineers concerned in plant design and operation. Many engineers have to deal with tricky problems without the benefit of the experience of people who have already grappled with the same problems.

I am very interested in availability, but cannot find in the paper any actual availability figures separated as between boilers and turbines. This should be possible as actual figures of breakdowns are included. The separate availability figures would be valuable because they would lead to the logical conclusion that, if the average boiler availability is lower than the average turbine

* Paper by R. W. Bruns and G. W. Maxfield (see 1944, 91, Part II, p. 276).

availability, future designs ought to provide increased boiler capacity so as to produce matched results when the availabilities are taken into account. I should like further information on this point.

The formula in Section 7.8 for calculating availability seems rather badly expressed, and is not mathematically correct. Would it not be better stated as the average availability arrived at by integrating the daily value of $(C_{a.m.} + C_{p.m.})/2C_i$ over 365 days?

Also, the authors make no allowance for the reduction in load at week-ends, when there is always a substantial reduction of load and advantage is taken to do minor maintenance work. I think the authors' formula gives a rather pessimistic result and in most cases it would be fairer to ignore Saturday afternoon and Sunday, when the week would include 10 periods only and the denominator for the weekly period would become $10C_i$, instead of $14C_i$.

Mr. J. D. Findlay: New plant installed during the period under review was 225 MW, approximately 40% of the total installed in 1938, but the average availability was only increased by 113·3 MW, i.e. approximately 26·7% of the 1938 capacity. In other words, the equivalent of half the new capacity was out of commission during 1942.

The authors give the ash content of fuel in 1942 as 16·6%. In the Midlands, it is about 20%, and some samples analyse as high as 40%; in some cases the output of high-efficiency plant has had to be restricted so that ash accumulations could be dealt with at off-peak periods to allow full capacity to be available for the peak-load next day. This may go on for several months.

I agree with the authors' figure of 10–15% loss of capacity due to unsuitable fuel, but this applies to all the stations. The loss at a particular station can be much greater and as high as 25% over long periods. Any one fuel or mixture of fuels has optimum conditions for most economic use, but when fuels are varying as they do now the boiler house cannot keep pace with the fuel changes; even structural alterations which the authors mention, however costly, cannot cope with continually changing fuels.

The breakdown analysis in Table 2 shows that the ratio of megawatt loss of capacity due to breakdown between minimum and maximum was 1 : 10 and that the maximum loss of capacity due to breakdown was 21·5% of the 1942 installed capacity. Condenser fouling is given as a breakdown, but I should rather consider this as a normal maintenance outage and comparable to boiler fouling which does not appear in the table.

In Section 7.8, the formula given for calculating the percentage availability excludes the night shift and lunch-hour periods, as well as the week-end period from midday Saturday to Monday morning. As an operating engineer, I find it is more difficult to obtain the necessary plant capacity for load during this period than during the week; in fact it is often necessary to take major plant items out of service from Friday evening to carry out the necessary maintenance or repair in time for load on the following Monday. If this were not done serious breakdowns might result at mid-week.

The authors consider base-load stations to have the advantage of more modern plant thus giving high availability, but this is counteracted to some extent by the fact that one item of plant in a modern base-load station may represent 50% of the installed capacity. Furthermore, these units have much larger capacities than in the older stations, consequently maintenance requires longer outages. My experience is that boiler overhauls require some six to eight weeks and sometimes longer with older boilers. This means that a station with eight or more boilers and only sufficient boilers for the turbines must have boiler plant out for survey during the winter-peak period or so arrange the work that two or more boilers are out for survey together during the summer period. To obviate capacity loss due to such summer outages, base-load stations must be over-boilered. Perhaps the stations with which the authors are concerned are not affected by shortage of maintenance labour.

In these days of continuous group operation, we have in effect one generating station with plant units spread throughout the country, the C.E.B. lines acting as busbars. The object of this arrangement is to generate electric current as cheaply as possible. I feel that the best comparison which can be made is one on a cost-per-unit basis. Whilst, say, station A has a high engineering efficiency, the purchase price of coal may be high, resulting in high cost per unit. Station B may have a lower engineering efficiency, but the purchase price of coal may be considerably lower than that of A. I suggest that station B should be the base-load station. I agree that engineering efficiency should be as high as possible, but account should be taken of what might be termed "site charges." High efficiency cannot be gained without high capital charges, and it may be that the benefit of high engineering efficiency is outweighed by the cost of attaining it. We must not lose sight of the fact that the ultimate financial results are those which show the real effect of our efforts.

Mr. H. S. Prosser: The conception of "operating efficiency" was mentioned in Mr. Lawton's paper* on Hams Hall "A" Station, read before The Institution in 1939. The curve in his Fig. 17 showed that this efficiency fell from about 97·8% when the station first started to 94·3% some years later when the installation was complete. This downward trend of operating efficiency as stations are extended seems to be general, and it would be interesting to know, with reference to Fig. 7 in the present paper showing operating efficiencies for a number of stations for 1942, whether in stations which had been extended the average operating efficiency for 1942 was less than for previous years.

I am very pleased to note the importance which the authors attach to running plant load factor. In an attempt to oversimplify the estimation of station efficiencies, the Parsons line has been too frequently pressed into service for a purpose for which it was never intended. It can be shown that

$$y = x\left(m + \frac{k_1}{CL}\right) + k_2$$

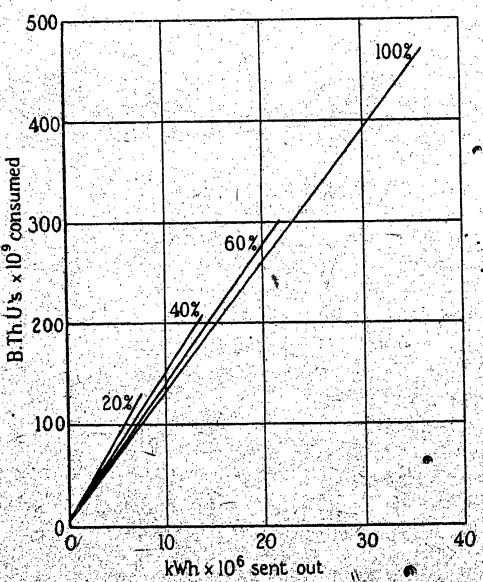


Fig. A.—B.Th.U.'s $\times 10^9$ consumed against kWh $\times 10^6$ sent out for running plant load factors of 20, 40, 60 and 100%.

* LAWTON, F. W.: "The Design and Operation of Hams Hall Power Station," *Journal I.E.E.*, 1939, 85, p. 469.

where y is B.Th.U. of coal consumed; x the kWh sent out; k_1 the no-load loss of the turbine, i.e. B.Th.U.'s required from coal to keep set turning at no load; k_2 the boiler banking losses, etc.; C the set capacity in kW; m a constant, and L the fractional running plant load factor of set.

It is evident that the B.Th.U.'s required for a given output are inversely proportional to the running plant load factor, so that plotting y against x we get a set of curves for the various running plant load factors as shown in Fig. A. There is nearly 5% difference in heat consumption between the maximum output at 60% running plant load factor and the same output at 100% factor, so that it is evident that any attempt to analyse or predict station efficiencies must take these factors into account, and any attempt to approximate by using the Parsons line where a range of load factors is involved will inevitably lead to discrepancies and misleading results.

Mr. C. H. Bottrell: The current need for fuel economy has directed attention to the thermal efficiency of generating plant, and if this paper will further stimulate the already live interest in the subject it will have served a very useful purpose.

The pre-war relation between fuel costs and capital costs is not likely to return after the war, and it is fairly certain that attention will be focused on the improvement of thermal efficiency even more so than is possible now.

Although outside the scope of the paper, it is as well to mention that the national economy will gain more with accurate group-loading allocation, or even national loading allocation, than is possible with independent station operation. It may sound paradoxical, but it is possible to reduce the thermal efficiency of every station in a group and yet improve the efficiency of the group as a whole. This would result, of course, on operating base-load plant above its most economic loading and so reducing the loading on the peak-load plant to its further detriment.

Table 1 is of particular interest in indicating the trend of design. The calculation of availability for over-boilered or over-turbined stations on the basis of the higher kilowatt capacity mentioned towards the end of Section 7.8 gives rise to the possibility of unfairness with the over-turbined station, since it is generally recognized that boiler outages predominate over main generator outages.

The conclusions in Section 10 are very interesting, but in the first conclusion (*a*) it seems rather drastic that pre-1930 plant should not be operated at above 45% average running plant load factor, as usually this type of plant is relegated for peak-load use, and it is generally expected to give loadings much higher than 45% of maximum during the running hours.

[The authors' reply to the above discussion will be found on page 576.]

WESTERN CENTRE, AT BRISTOL, 14TH MAY, AND AT CARDIFF, 15TH MAY, 1944

Mr. S. Hartland: The authors suggest that the months of April and October had better be watched, thus implying either that a movement of the peak was taking place or that it was "levelling" well beyond the four winter months. Would they clarify this statement? How is this related to the present tariff structure, whereby demand charges are made only on the demands registered in the four months January, February, November and December?

Mr. D. P. Farrant: The scope of the paper is so wide that it should provide material for thought for a long time. I particularly appreciate the authors' effort to assess the responsibility of the various departments for the various types of failure. This is always a vexed question in central stations.

With regard to the target efficiency scheme, while I appreciate that, for a start, the simplest scheme is the best, I feel that there are many unavoidable factors which are not allowed for. These factors may lead to erroneous comparisons, and it is to be hoped that, as experience is gained in operating the scheme, more and more of these factors will be taken into consideration.

Mr. R. H. Bent: The calculation of operating efficiency fills a need that has been acutely felt by all station engineers for years past. It is a yard-stick whereby not only can the performance of one's own station be watched, but useful comparisons can be made with other stations.

The new method does not, however, appear to be perfect. There seems to be some elasticity in the yard-stick, and no doubt further allowances and adjustments will have to be introduced according to experience. At the plant with which I am connected, the best operating efficiencies are obtained with half the plant out of commission, thus requiring a heavy load-factor correction. Thus it appears there is some incentive to take plant out of service in order to get a better figure, but the introduction of a plant availability factor will no doubt correct this.

In due course we shall have a spare boiler. How would plant availability then be calculated? For, should one particular boiler develop a defect, the spare one will be brought in and station output will remain unaffected.

Regarding an age-of-plant allowance, which was taken into consideration, is this not a difficult matter to deal with, as some plants wear much more rapidly than others? Thus a well-kept plant, which has withstood the buffetings of the war years, would probably obtain an allowance which would make its results fantastically high.

Mr. B. S. Gylee: The work involved in the routine calculation for operating efficiency is very simple. In the station I represent, we have instituted the calculation as a weekly routine, as we find it to be of considerable encouragement to the efficient running of the plant. I suggest that a more equitable assessment of the banking allowance would be made by adjusting the basic allowance in the ratio of the calorific value of the fuel to that on which the basic allowance was calculated.

Mr. H. V. Pugh: I am sure that all the power-station engineers connected with the stations from which these data were compiled agree that the authors have made a very useful contribution to the study of the efficient operation of power-generating plant. A considerable measure of success had already been achieved, and the future will show much greater improvement.

It is possible to criticize the standard for operating efficiency based on the overall efficiency ratio curve in Fig. 6. I had hoped it would be possible to get another basis which would bear some relation to the type of plant in any particular station. While the method outlined in the paper is a fair basis of comparison for all classes of power stations, I feel that the smaller stations, even though operating on a single- or a two-cycle shift, are favoured by certain minor aspects of the method adopted.

Mr. T. R. Evans: What would the authors consider from long experience the most economical size of generating station to erect, water, coal supplies and position being equal?

I wonder whether the authors are aware of the interim report recently presented by the Welsh Reconstruction Advisory Council to the Ministry of Fuel and Power, dealing with the national load factor of electricity supplies, which states that before the war our electricity generating and supply plant was much unused, the load factor being only about 34%, and that if collieries produced coal for nothing and railways carried it free the total reduction in the price per unit which could be made would be no more than could

be obtained at this very moment by increasing our national load factor from 34% to 40%.

Mr. J. Vaughan-Harries: Are we correct in assuming that the data collected by the authors cover generating stations burning different fuels, namely anthracite coal, dry steam coal, a mixture of anthracite and dry steam coal, and other fuel? If so, would the authors state what would be the percentage of units used at the station to the number of units generated? It would be very useful if the character and size of each station could be given, together with the information asked for, in the form of a table.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. R. W. Biles and G. W. Maxfield (*in reply*): It is hoped that Mr. Burge's recommendations will be adopted when normal times return; to do so now during war time would unduly increase the work of station staffs. Our proposals are based upon technical performance rather than costs, which vary considerably for a number of other reasons and therefore complicate comparisons.

In reply to Mr. Berridge, the stations under survey did not use a uniform method of sampling, but the testing was as uniform as present-day laboratory conditions permit. The fixing of an overall efficiency ratio by age was decided on for simplicity. An alternative based upon heat rates and losses may be better, and so long as the method is uniform for all stations, no objection is raised. The suggestion regarding Mr. Priest's factor would be taken care of by adopting Mr. Burge's proposal.

We are in accord with Mr. Sayers and would welcome separate records of turbine and boiler availability. Our method urges investigation when availability is low, and helps to ascertain what extra boiler margin is required. We have found the availability formula satisfactory, as it takes account of minor restrictions and restricted running.

We agree with Mr. Findlay that fluctuations in the quality and grading of fuels make the highest efficiency impossible, even on the best equipment. Condenser fouling is treated as a breakdown only when the outage was precipitated without notice. Both condenser fouling and boiler fouling are reflected in the availability result. The availability formula does include the week-end, for the reason Mr. Findlay gives. Load dispatching is done in accordance with production cost, quite distinct from operating efficiency.

Mr. Prosser's formula is quite in accord with Fig. 5 when it is remembered that his k_2 is deducted in the process. Operating efficiencies have not generally fallen when extending stations, except in the first few weeks of commissioning new plant.

In reply to Mr. Bottrell, overall economics will determine the output from the older plant. Full availability of such plant should be ensured during the highest winter peaks. This demands a rather easy loading in the remainder of the year. Conclusion (*a*) in Section 10 is supported by Fig. 8.

In reply to Mr. Hartland, we know of no appreciable change in the shape of the annual load curve. The availability of plant tends to fall away in April because of the need of overhauls, and in October because overhauls have not been completed on programme.

In accordance with Mr. Farrant, we have tried to evolve a system giving the minimum work to station staffs. A higher accuracy is obtainable by expanding the system showing more internal detail (irrespective of station comparisons), which we hope will be developed in due course.

The plant Mr. Bent refers to has probably a false low-target efficiency at present when one of its two boilers is off, and may be due to the method, presuming that each turbine is backed by two boilers. It may be necessary to adjust for this condition in some cases, by using l.f. correction curves for turbines and boilers separately. Regarding availability, the system proposed urges an inquiry by the method of comparison. If the cause of a consistently low figure is found to be beyond the control of the operators, suitable action can be taken. We are inclined to base availability on effective station capacity.

We agree with Mr. Gylee that the banking allowance should be adjusted in the ratio of calorific value; such steps are being introduced.

In reply to Mr. Evans, we consider there may be no limit to the economic size of a generating station except that of adequately loading it, providing water, coal supplies and position are equal. During the past few years station capacities have been limited to 150 MW according to their position.

In reply to Mr. Vaughan-Harries, the records include data for all kinds of fuel, with South Wales fuels predominating. Consumption for auxiliaries is 3 to 4% in the older plant, 6 to 8% on the 400 to 650 lb/in^2 plant and 7·5 to 10% in modern stations using pulverized fuel, varying with load factor of main plant.

DISCUSSION ON

"MAINTENANCE OF DISTRIBUTION PLANT AND MAINS ON A.C. NETWORKS"*

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 11TH JANUARY, 1944

Mr. T. D. Oswald: The recent report on electrical accidents in factories describing an accident on a power-station busbar emphasizes that the rigid enforcement of a comprehensive routine system of safety precautions is essential for the safe operation of high-voltage equipment. The "permit-to-work card" system advocated by the authors has been operated satisfactorily by undertakings with which I have been associated. Experience indicates that the following should be made an integral part of the system: (*a*) proving of allegedly dead apparatus by a neon indicator in the case of bare metal, or spiking in the case of cables; (*b*) locking-off of apparatus by distinctive locks, the sole available keys of which are accessible only to the person engaged on the work; (*c*) the clear indication of live parts and adjacent equipment which may be in operation, by the use of "Danger" notices, and (*d*) the return of the card, signed by the person engaged on the work, certifying that men have been withdrawn, before making alive is permitted.

The hermetically-sealed transformer installed in an underground chamber, entirely without ventilation, is interesting. Experience during the war has shown that existing indoor transformers with Grade "A" oil are prone to increase in acid content in normally-designed substation buildings, in which ventilation has been restricted by the blackout. The replacement of the oil by Grade "B" has made an improvement in these cases. Even Grade "B" oil might tend to become acid if kept at high temperatures for long periods. Further information regarding the design of the transformers used in underground unventilated substations, the loading cycle, and the temperatures of transformer oil and ambient air would be of value.

Mr. J. E. McV. Calwell: I agree that the maintenance staff should, wherever possible, carry out the installation of new equipment. This staff should also be thoroughly reliable and conscientious. If not, what appeared to be a record giving a satisfactory picture of the health of plant installed might be quite false.

Many years ago the company with which I am connected adopted Grade "B" oil in transformers in place of Grade "A," on the score of economy, as it was considered that Grade "B" was satisfactory enough. It is gratifying to note that recent experience has shown Grade "B" to be the more satisfactory oil from the acidity point of view.

Section 9.2 states that new plant is brought slowly up to normal voltage before being connected to the system. Referring more to overhead and underground cable mains, I should like to know whether the authors have dispensed with tests specified by the Electricity Supply Regulations to be carried out before such plant is brought into service.

I was interested in the underground transformer, but could not follow the details. Would the authors state whether the transformer tank itself is the hermetically-sealed item, and whether the surrounding tank containing the connections from the cable boxes to the transformer tank is oil-filled or merely air-filled?

Mr. M. Hanna: The review of the economics of maintenance is well balanced throughout the paper, as the maintenance engineer has not only to consider a suitable programme of maintenance, but also, what is the minimum required consistent with continuity of supply. It will be agreed that switchgear maintenance is a specialized class of work, and necessitates careful training of the workmen.

I have had experience of two types of filtering plant: (1) a filter press using heavy absorbent paper in compression, and (2) the meta-filter type. Each has disadvantages, particularly the second, and the authors' opinion as to whether the centrifugal type is not on the whole the best would be helpful.

Sampling oil from transformers on load can be a very unpleasant job. On one occasion, I had to get a large number of samples from different transformers. A length of hose pipe was passed down the stand-pipe of the transformer, and a syphoning action started by means of a bicycle pump and a reversed football valve; this gave a reliable oil sample from the bottom of the transformer. The smell and colour of the oil, the presence of suspended particles, and the breakdown voltage, should be stated on the oil-test report, in addition to the degree of acidity.

When a transformer is being replaced it should be given a fairly comprehensive overhaul, which should include the following: (1) lifting the transformer core out of the tank; (2) taking up any shrinkage of the coils by means of the coil-tightening bolts; (3) tightening up every nut and bolt on the transformer core and connections; (4) filtering the oil into clean drums; (5) removing foreign bodies from the tank; (6) cleaning down the transformer core and tank with oil; and (7) examining the tapping switch to see that contact is made on each stud, in the case of manually-operated off-load tap-changing gear. With regard to the last point, it is possible for an open circuit to exist on one phase of the high-voltage delta-connected winding and for the transformer to continue to supply the three-phase low-voltage network. Normal overload and earth-leakage protection would not operate on a fault of this character, and very puzzling phenomena can accompany it, unless the possibility is kept in mind. In the supply company with which I was connected, three such faults occurred in approximately eleven years.

[The authors' reply to this discussion will be found on page 583.]

* Paper by E. N. BEAUMONT and F. A. GEARY (see 1944, 91, Part II, p. 108).

SCOTTISH CENTRE, AT GLASGOW, 8TH FEBRUARY, 1944

Mr. J. Henderson: It is a great pleasure to listen to a paper advocating the keeping of good and complete records. The question is whether one should keep too many or too few records. If too many records are kept a much bigger staff is required and this adds greatly to the cost of maintenance.

Two kinds of records should be kept—routine and design—and they should show the results of all tests carried out. Design records should be provided by the manufacturers, and in this I have always been a great advocate of standardization. At the present time, each manufacturer has a different test certificate,

and I think these should be standardized so that in every case the same items will appear in the same place.

A significant omission from the paper is metering, perhaps because it has been standardized. Yet it is standard practice to provide test certificates for meters and current- and voltage-transformers, and I cannot see why the same scheme should not be applied to power transformers, relays and even cables.

A great deal could be done in the elimination of records if standardized wiring schemes were adopted. If colours for wire and fuses were standardized, every panel would be its own blue-print; this would save a great many paper records.

Safety precautions are in many cases not as effective as they might be. The adoption of "permit-to-work" cards is essential. Many accidents are caused by the short-circuiting of the safety precautions which have been laid down. The authors recommend that conductors which have been alive, for work or for any other purpose, should be earthed through a circuit-breaker, but as the latter may not be making contact, the conductors may not be earthed at all. Wherever possible, live-conductor detectors should be used and when conductors are found to be dead the earthing connection should be applied directly. I think that the use of these detectors will ultimately be compulsory, but before this can be done a considerable improvement and alteration in the design of switchgear—particularly metal-clad switchgear—is necessary to enable such detectors to be used with safety.

Mr. A. F. Stevenson: I suggest that the armouring of cables should be bonded to the lead sheathing. I have known pitting of the lead due to arcing from the armour during a heavy fault. The authors are to be congratulated on having so little trouble with their h.v. cables. Have they stressed them periodically with h.v. direct current as is the practice in some systems? I am surprised to see in one of the diagrams a reference to a 0·4 four-core l.v. cable. This is a most undesirable form of distributor, which is not included in their standardization scheme.

Mr. W. Easton: The paper deals with maintenance problems on a large city network of ample capacity and carrying a considerable reserve of plant. A routine maintenance programme drawn up to meet such circumstances differs considerably from that required for a smaller undertaking with a low load density where much of the plant cannot be taken off load, except overnight or at week ends. Maintenance arrangements for such undertakings must be very flexible and must be governed by the availability of both plant and staff.

Surely, progress in the design of equipment will steadily diminish the need for maintenance as weaknesses are found and remedied. Some purely static plant, such as transformers and switchgear, subjected to little wear and tear, have been examined after long intervals and found to be as free from defect as equipment being regularly examined in expectation of trouble. The probabilities and consequences of breakdown must be considered in conjunction with the costs involved, and it appears that each undertaking must develop its own maintenance programme with these considerations in mind and arrive at a scheme of its own, most suitable for local conditions.

Mr. A. McKorn: I agree with the authors on the regular operations of switchgear; apart from "mechanical settling" there are secondary circuits and relays which are vulnerable even to dirt on the contacts, and the only assurance that they will operate is to test them at regular intervals.

Mr. W. Rowan: I should like the authors to say whether transformers installed in underground pits are reliable in service, and whether they require frequent maintenance. I noticed from one of the slides shown that the voltage was 3 300 volts. Do the authors expect the same reliable service from higher-voltage equipment, say 11 000 volts?

Mr. F. J. Bell: Speaking of tripping batteries, the authors have referred only to secondary batteries. I would like to ask their experience as to the general efficiency and the maintenance necessary with primary batteries, such as Leclanché cells.

The greater maintenance cost of cables drawn into ducts has been mentioned. What is the reason for this? Is it due to greater electrolytic troubles with cables in ducts, as compared with direct-laid cables? I have had considerable trouble in my section, particularly with light relay and telephone cables, the lead sheathing being perforated and eaten away by electrolytic action, obviously due to tramway currents. Is it not possible to minimize this trouble by earthing the sheathing of the cables at frequent intervals?

I am disappointed that the authors did not deal with the latest methods of fault location. We all know of the elaborate apparatus now provided for the localization of high-voltage faults, but many undertakings still locate their low-voltage faults by pick and shovel methods. The use of small multi-range test sets capable of taking a loop or a p.d. test would be quicker and more efficient for this purpose.

[The authors' reply to this discussion will be found on page 583.]

NORTH MIDLAND CENTRE, AT LEEDS, 22ND FEBRUARY, 1944

Mr. R. H. Grafton: The paper is of special interest to those engineers who are responsible for the continuity of supplies on a.c. networks, such continuity depending largely on the regular maintenance of plant and mains. Before such work can be undertaken, close consideration must be given to those safety measures necessary to protect the personnel concerned, hence I fully agree with the comprehensive safety precautions outlined by the authors.

"Permit-to-work" cards would have greater significance if, before signing the card, the person receiving it were instructed to read aloud its contents and to check that all the safeguards mentioned therein had been carried out.

Increased security for persons working on high-voltage apparatus can be afforded by using a lockout key box to hold the keys which lock-off switches or isolators controlling supplies to the apparatus on which it is desired to work. This key box should be secured by a lock having one key only, the key being held by the person in charge of the work, so that while it is in his possession the apparatus on which he is working cannot be made alive. The key should be surrendered when the "permit-to-work" card is cleared.

The keys used for locking-off switches on a switchboard should be non-interchangeable and properly labelled, so that padlocks on one switch cannot be unlocked by keys for another switch, and as indicated by the author the use of master keys should be strictly forbidden.

Reference is made to the earthing of high-voltage feeder or transformer cables through the associated automatic oil circuit-breaker. Earthing circuits by racking-in and closing an oil circuit-breaker, after fitting extension pieces to the feeder plugs and earths to the busbar plugs of the switch, is a valuable safety measure, as opposed to the fixing of earths by hand direct to the spout contacts. Should the feeder be alive, utilizing the breaker not only protects the operator from serious accident, but also avoids a flashover to earth from the live spouts to frame. For the safeguard to be effective, it is important for the alignment of the extension pieces to be accurate so that these pieces do not foul the contacts when the switch is racked-in; also the extension

pieces should be rigidly secured to the switch contacts to avoid fouling of the spout contact and the possibility of the contact being left behind in the spout when the switch is withdrawn. In addition, the extension pieces should be insulated or so designed that there can be no flashover to earth should the feeder contacts be alive.

The authors mention the use of detectors during the operation of cellular switchgear. Live-conductor detectors have a valuable application as a safety precaution in checking that conductors are dead before earths or test leads are applied to them. They should be used as a last line of defence against error and after all possible visual checking of designating labels has been carefully carried out.

Regarding the safety precautions to be followed with fire-fighting installations, where there is no danger of maintenance personnel accidentally operating CO_2 detectors I would ask the authors whether they consider it necessary to shut off the CO_2 in every case whilst work is being undertaken on plant protected by the CO_2 installation.

Mr. H. Hurworth: I should like to emphasize the author's insistence on the strict observation of safety precautions, particularly when apparatus is made dead for repair or maintenance work, but I do not consider that the "permit-to-work" card system is the best method of ensuring safety. In my opinion it is weak, because it relies too much on the integrity of authorized persons. It assumes that a satisfactory standard of safety can be achieved by ensuring that the operator knows when supplies can safely be restored, and by providing a means of emphasizing to the authorized person that by signing the card he is made responsible for the safety of the workman.

That is insufficient. The apparatus to be made dead is described, but provision should also be made to ensure that this description is understood by the workman. The card does not safeguard the workman against the possibility of future operations making the apparatus alive inadvertently. Security from accident owing to this possibility depends on the care and accuracy of the control staff, and on additional precautions such as the removal of keys. On a modern system with complex switching arrangements, it is rare for the workman to realize what steps are necessary to secure his safety; therefore under most "permit-to-work" card systems, he must rely on the work of an authorized person whose procedure and instructions may not be checked. Accidents are bound to occur sooner or later, if no arrangements are made to enforce a reliable system of checking the procedure at each stage of the work. It is easy for the most conscientious person to make a mistake, particularly if he happens to be distracted by worries. Many accidents have occurred in recent years through distracting influences, and the Annual Report of the Factory Department has thought it desirable to draw attention to several cases of accidents which might have been avoided by a system of checking.

A very high standard of safety has been maintained during the last thirty years on one of the largest undertakings in the British Isles, by making two individuals separately responsible for the safety of each operation, one person thus checking the work of the other. Each stage in the process of arranging and carrying-out the work is checked. The workman is given full details of the switching and earthing procedure, in addition to exact particulars of the work to be done. He is made personally responsible for checking each of these operations and is trained to understand his part in the procedure.

The detailed instructions he receives are prepared in duplicate by a third person, and a copy is handed to the authorized person with an additional instruction that the operating procedure requires checking. Finally, all keys belonging to the locked apparatus are transferred to the control of the workman, so that no subsequent operation can be carried out on this apparatus without his permission.

This cross-checking of the procedure at each stage encourages attention to the work and eliminates slackness. The workman appreciates his part in the system of checking, whilst the authorized person will take particular care to avoid operational errors when he knows that a mistake of this kind will be detected by a workman.

During the time these methods have been in use no accident has been caused either by switching errors or by mental distraction.

Mr. R. H. Coates: The authors could justifiably have given the question of records even greater prominence than they have done. The following example shows how much time and work they can save.

In 1932, I spent seven months doing commissioning tests on the N.W. England Grid substations. For a standard three-switch substation fully 400 different tests were necessary; in the absence of a system at the start, it took three weeks to complete each station, and the records of the work done were almost too involved to be intelligible. In re-organizing the work, the tests were split up on a decimal system, all tests of one type being 101, 102, 103, etc., the next type 201, 202, 203, etc., and so on. Sheets were duplicated to receive the results of tests, schematic diagrams were prepared, and the exact location of the testing transformer in the substation was fixed so that the heavy test leads were kept as short as possible. The sequence of tests was worked out to minimize the change of connections and position of oil circuit-breakers, and to prevent as far as possible a later test showing up a fault requiring previous tests to be repeated. The whole scheme was bound into a book for each substation, complete with diagrams and notes as to previous troubles, and was formally known as "T.T.T." (Tips for Tired Testers).

When we got into our stride we could do a complete substation, with an accurate record of every test, in three days. Not only could we do the tests quickly, but very much more intelligently. Halfway through a substation we did not have to think what to do and how to do it; it was all written down beforehand, and if any piece of apparatus behaved other than as the designer intended, we could give our full attention to what was wrong.

The authors question whether commissioning work and routine maintenance work should be carried out by the same personnel. I think this depends on the size and type of work, since much maintenance is humdrum work and the type of man best suited to it may not be best for commissioning new equipment, and vice versa.

Section 5 refers to earth-fault indicating lamps on the control circuits. These are a very real danger, since they pass sufficient current to operate relays and produce, in effect, an earthed system. In Sheffield we have developed a super-sensitive earth-leakage alarm (British Patent No. 539839) which sounds an alarm when the insulation resistance falls to 20 000 ohms; but even with this equipment we found that since some switchboard relays operate at 10 mA we had, in effect, an earthed system, and with a single earth a relay has been operated by the leakage current of the earth detector. To retain the advantages of continuous leakage detection and of an insulated system, we specified a minimum current for any relay of 50 mA.

In 1931, at Grove Road power station, where the authors were installing busbar equipment of the type shown in Fig. 5, an earth fault on the trip bus wire together with an earth fault on a positive feed to some d.c. works power equipment operated every tripping relay on the board. The equipment was not connected for tripping the oil circuit-breakers so no harm was done, but it illustrates the benefit of continuous leakage supervision and also one of the weak points of the scheme of Fig. 5.

In Section 7, the authors say that the economies of low-loss transformers justify a 20% increase in cost in view of the greater saving in maintenance costs. It would be of interest to have complete details in support of this statement.

Dr. J. McCombe: There are a few important matters which the authors have omitted. Having been associated with two large undertakings covering 3 000 sq. miles, I have found the two most important items to be communications and transport. For intercommunication it is doubtful which is the better, the private telephone system or Post Office lines. Most firms have compromised and use both. Regarding transport, I have found that, in order to find faults quickly on a remote part of the system in difficult weather, vehicles should be so placed that the maximum distance to any district boundary is about 12 miles.

Mr. W. Fordham Cooper: In my view the object of "permit-to-work" cards is twofold. First, the cards should indicate exactly which situations are safe and which are dangerous; secondly, they should indicate exactly what work is to be carried out. It should be a breach of rules either to enter or to approach a locality which has not been described as safe, or to undertake any work not included in the instructions. If other work has to be carried out either the permit should be amended or, preferably, a new permit should be issued. All persons concerned should know precisely what is the work in hand and what may be done, and should refuse to do anything not covered by their permits and be protected against disciplinary action if they do so refuse. I have found that permits are not always taken sufficiently seriously, and suggest that senior engineers when visiting a site should always ask for the permit and then, when they have it in their hand, ask appropriate people what it covers to see that it has been properly understood. I feel that something approaching military discipline is required for safety in work on and near live h.v. equipment. There must be no possibility of a mistake.

With regard to Castel keys, master keys should be used only in an emergency, and then only by, or on the direct instructions of, very senior officials. At all other times they should be kept under lock and key, and not be available to charge engineers or other persons about the power station without breaking a seal or forcing a cupboard, or some other obvious action. After one serious accident it was found that all the charge engineers at a station had made their own master keys.

Regarding the testing of switch oil, I do not think breakdown strength as ordinarily tested has any *direct* significance. The clearances adopted in all good switchgear are far in excess of those at which even the dirtiest oil would break down. The major importance of this test is as an indication of the contamination of the oil by moisture, carbon or other material collecting in a gap or settling on an insulating surface.

Bus-zone protection is in very general use in this part of the country, and up to the present I have heard of none of the troubles due to instability which were so generally feared. I should like to have some information on the authors' experience in this connection.

Mr. J. Mann: What are the authors' objections to inter-mixing maintenance and erection staff? With us, maintenance staff are derived from the erection staff and vice versa. I have found this method to work very satisfactorily and it makes the men thoroughly conversant with the activities of both sides.

The "permit-to-work" system should be supplemented by a personal lock so that each maintenance man has his own lock and own key. A duplicate key should be kept locked away. I have found this method very satisfactory from the point of view of the safety of the workman doing the maintenance.

Mr. G. H. Sammons: Experience up and down the country has given me very decided views on the question of record cards, for I have scrapped several record-card systems because they were useless. The cards put forward by the authors look very attractive when new; I would prefer to see cards several years old with the records engrossed thereon. In other words, the value of a record card is not in the layout, column headings, etc., but in the written information. The most important factor in any card system is that it is nearly always out of date. A card made out to-day is out of date to-morrow, and unless very strict watch is kept on entries, card systems are more nuisance than they are worth.

I must congratulate the authors on the layout of the mains records plans in Figs. 6 and 7. It seems to be most difficult to persuade a mains draughtsman to reserve road space for essential information, and to put all ancillary information on the building space.

The routine testing of cables is still a matter of controversy. In Birmingham, routine testing of cables is undertaken, and incipient faults are found and duly repaired. In Manchester, cables are left until they fail. On the whole the ultimate reliability of each system is about the same.

[The authors' reply to this discussion will be found on page 583.]

NORTH-EASTERN CENTRE, AT NEWCASTLE-UPON-TYNE, 27TH MARCH, 1944

Mr. E. C. I. Macdonald: This paper is especially valuable as a compendium of information, compiled from practical experience, on matters on which little has so far been published.

The question of combining new construction staff with maintenance staff can be argued both ways. I favour separation, provided there is a satisfactory degree of collaboration in the light of operating experience. A construction staff pure and simple can view troubles in a detached way, is more free to study new developments, and is not hampered by a subconscious feeling that expenditure must above everything else be related to current revenue.

On a large system the number of copies of records should be kept as low as possible. There should be one master record, but control engineers should have information in advance of the records. Staff should never be allowed to assume that because standardization has been carried out, records are unnecessary.

What loading per cubic foot do the authors use for switch-room heating? I am glad that they favour the elimination of plug-and-socket junctions for auxiliary circuits on switchgear.

Batteries although amongst the most important accessories on the system, are sometimes the most abused. Unnecessary wear and tear and early failure may result from "playing safe" by setting the trickle charge at too high a rate. Recent developments in metal rectifiers bid fair to offer an alternative and less vulnerable source of small power, where mains supplies can reasonably be used.

The authors' load checking equipment seems admirable but costly. Have they any experience of a simple thermal-type load indicator with a characteristic approximating to that of the transformer? I agree that load factor could not be estimated with this type, but I assume such complete data are not expected in any but relatively heavily-loaded urban areas.

Have the authors found any difficulty in relating the rating of h.r.c. fuses to the overload it is desired to handle, as well as to the ultimate safe loading of the transformers?

Do they find inverse time over-current relays worth while at in-feeding points, in addition to balanced protective gear? I suggest that a considerable saving on relays and maintenance

could be effected if over-current protection were restricted to outgoing feeder switches. Much of course depends on the system connections. Do the authors take any special precautions in bonding or earthing cables near electrified railways?

I endorse all they say on keeping the number of sizes of cable to a minimum, and their selection entirely confirms my own experience. It must be remembered that the cost of installing the next larger standard size of conductor, e.g. a stock 0·25 in^2 instead of a 0·20 in^2, is usually a very small proportion of the total cost of any given cable installation, and is amply covered by the saving in stock types required.

Mr. F. E. Heppenstall: The authors have rightly emphasized the importance of safety regulations, but have made no reference to the use of a search-coil test to locate cables, a device that gives additional safeguard.

The maintenance schedules given are very complete, but it is to be hoped that a certain amount of discretion is exercised over the length of maintenance periods concerned with such work as switchgear cleaning, routine operation of circuit-breakers, transformer-connection inspection, acidity tests, etc. In many cases there is little reason for carrying out this work very frequently.

The use of integrating meters with M.D. attachment has been found very helpful to give maximum substation loading and load factors.

Caution should be exercised in relay tests involving the removal of relay leads, and the cleaning of contacts on time-limit fuses is important for reliable operation.

Have the authors solved the difficulty of lifting pavement lids in frosty weather? What compound have they found most suitable for this duty?

Mr. J. E. Lambert: The routine maintenance of transformers, etc., as outlined by the authors is similar to that carried out in this district, with the possible exception of the time factor. For the purification of oil, we use the centrifuge-blotter press and the filter pack, both with cold filtration, and with the oil heated before filtration. Experience shows that each has its good points, depending on the nature and quantity of the foreign matter to be dealt with. Heating the oil before filtration is limited to major substations, as the electrical loading of this type of purifier is too high for the kVA capacity available at smaller substations. Experience shows that deterioration of the oil is accelerated by heavy loads and high working temperatures.

Experience in this district with regard to the sludging and acidity of oil is similar to that reported by the authors. We have had no difficulties with excessive sludging or acidity on transformers fitted with conservators, only periodical filtering being necessary. Self-cooled indoor transformers are more prone to acidity than outdoor, probably because of less efficient ventilation. It is important that the rise of acidity as well as its value should be carefully watched, for experience shows that after reaching 0·5 mg KOH per gramme of oil as given in Section 6.1.2 (*c*) and (*d*), the rate of rise increases. A unit at present under observation had an acidity value of 0·44 mg KOH per gramme of oil in September, 1943, after about 5 years' service. The acidity value in March, 1944, was 0·96 mg KOH per gramme of oil.

I agree with the authors' comments in Section 6.1.2(*e*), but would add that, in our experience, once an oil has reached an excessive acid value, the effect on acidity of purification by centrifuge or filter is very small, even when using marble and granulated carbon.

We replace acid oil by new oil from stock, but to do this satisfactorily the transformer should be withdrawn from service, if possible. If the acid oil is simply pumped out on site and replaced by new oil, the latter very quickly becomes acid from contact with the windings and tank. The better procedure is to lift the windings and to wash them with clean oil under pressure, to scrub the inside of the tank and cover it with hot soda-water and then clean water, and then to put both windings and tank into a vacuum oven. After drying, the unit is re-assembled and filled with the new oil.

Regarding the return of the acid oil to refineries where it can be treated at a small cost, would the authors give some idea of the number of gallons which will be accepted for treatment in one lot? Have the authors any experience of the purification of oil using activated alumina?

Our maintenance routine for tap-change transformers is on the same lines as that of the authors. We use portable drainage tanks, as from experience it is advisable to avoid using a large number of oil-drums wherever possible. If oil-drums are employed, then two sets should be in use, clean and dirty, and easily recognizable, and regular use should be made of an oil-drum washer.

Table 2 contains the item "Inspect explosion diaphragms, replace fractured ones." Would the authors give their experience of the material used for this purpose? We have experience of copper, aluminium, glass, celluloid and Tufnol, none of which is very satisfactory from a weathering point of view.

Mr. W. Dixon: Whilst cold filtration of oil may be desirable, we have found in practice that oil heated before being purified has given satisfactory results, and there is of course a saving in time. The statement that the centrifugal cleaner requires special processing when dealing with carbonized oil presumably refers to oil containing colloidal carbon. Our experience has been that the filter purifier will not operate for a long period if the oil is very wet or very dirty. The authors, on the other hand, recommend that Penetrol should be heated before being purified. Is there any difference in the amount of impurities likely to be dissolved in this oil as compared with the more fluid oil?

With regard to power factor testing of insulators, it is important that such tests should be carried out and a record kept for each insulator, as the actual value of power factor is not so important as a change in value.

I should be interested to know the authors' experience of the comparative life of lead and alkaline batteries, and how their maintenance costs compare. The proposal to use a portable spare battery is useful in a rural area, but hardly applicable to the larger substations where a solenoid current up to 500 amperes may in some cases be needed.

It is suggested that acidity can be checked by the purification of the oil by a centrifuge or filter. I was under the impression that it was difficult to remove acidity from oil by this means, and that the oil has either to be washed with water, and the water either removed by the centrifuge and treated with prepared alumina, or returned to the refinery for treatment. I would like to have the authors' views on this.

It is suggested that the tap-change units should if possible be divided so that the selector switches are in one oil compartment and the others which make or break current in a separate compartment. This should reduce the amount of maintenance.

In Section 6.2.3 the authors state that silica-gel breathers are partly regenerative. I am not sure what that means, as when silica gel absorbs all the moisture it can that moisture can be driven off again by heat treatment and the gel should then recover its original condition.

The statement that it is possible to reduce iron and copper losses in transformers by as much as 40% at no more than 20% of normal transformer costs begs the question. What are the figures of losses and the cost of the original transformer?

With regard to oil-filled cable maintenance, I would very much like to know whether the authors have any views on the cost

of maintenance of such cables as compared with that of the H-type of cable, particularly for 33-kV? At this voltage both the H-type and oil-filled cables are satisfactory from an electrical point of view, and a decision on the type to be used has to be made on the basis of first cost and maintenance costs.

Mr. J. S. McCulloch: To overcome the difficulties mentioned by the authors of finding continuous employment for new installation work, I would suggest it should be handled by outside contractors, but overlooked and watched by the maintenance engineers. In a large public-utility organization, I cannot see that it is economic or efficient to have the maintenance staff actually doing new installation work.

The "permit-to-work" card system described is used on most large undertakings, but occasional fatalities still occur. I feel very strongly that the number of fitters and non-skilled men allowed to be under the charge of an authorized person should be stated on the card, and that the number so allowed should be kept low.

The advantages of a continuous trickle charge are now admitted, but I have heard maintenance engineers state that batteries so maintained and which have little load drawn from them, are much improved by an occasional "full-rate" discharge apart from the two-yearly discharge to obtain test data. What is the authors' opinion?

I was interested to learn that the authors advocate the use of h.r.c. fuses for overload protection. As the thermal characteristics of these fuses do not follow the thermal characteristics of transformer insulation, I shall be glad if the authors will state how they provide sustained overload protection and yet prevent the transformer from inadvertent tripping on short overloads of a higher value which do not have an adverse effect on the transformer insulation.

In these days it is difficult to obtain the use of an isolated generator for commissioning tests on protective gear. I am surprised the authors do not advocate the use of a portable low-voltage primary-injection set. Almost all maintenance protective-gear installations can be commissioned with such a set, the only exception I have met being where current transformers are installed in the h.v. bushings of transformers.

In Section 9.3.2, I think the authors might have stressed the necessity of avoiding the removal of protective gear wiring from terminals for the purpose of tests. Testing sets should be designed to avoid this; the practice of bringing relay wiring to the front of panels into link boxes is to be highly commended. The authors mention links only in connection with the ends of pilot cables.

In Section 9.3.3, the authors rightly stress the importance of checking the timing of injection-type relays. I would suggest that the usefulness of a secondary-injection set would be improved by the incorporation of a synchronous timing device. Such a device would not unduly increase the overall dimensions or weight of the set. It could be connected so that it started on application of the secondary fault current and stopped on the closing of the relay contacts or, if required, the opening of an auxiliary switch on the circuit-breaker mechanism.

Mr. L. A. Bates: I am chiefly interested in mains, and I would like to raise one or two points relating to them. I am surprised that the design number or drawing number of the joint and the termination used are not included in the record in Fig. 9. This information can be very important as time goes on, especially if replacements are called for or if trouble due to defective design is experienced.

The authors say that, to prevent the spread of gas along a duct line, the ducts are sealed at one end of each run. Is this intended to be a permanent seal, or is it only to restrict the passage of gas? I should be grateful for some information of the methods employed.

Reference is made to electrolysis in cable runs, but the authors do not indicate to what extent this trouble occurs. Assuming that the cables are not laid in a waterproof duct, have they tried other methods of dealing with the trouble, and if so have they met with any degree of success?

As regards the maintenance of oil-filled cable, we have only recently installed automatic oil-leak indicators on a number of 66-kV feeders. As we have not yet formulated our final maintenance routine for these feeders, I am very interested in the scheme the authors have adopted in their area. I agree that permanent oil-pressure gauges, especially in underground pits, are very liable to error, and one would like to dispense with them entirely, provided one could be reasonably certain that the oil-leak switches could be relied upon and their operating characteristics remained satisfactory. We have not yet had sufficient experience to say whether this is fairly certain to be the case. I assume that the authors have a number of feeders not provided with automatic oil-leak indicators, and I should be glad of some information regarding the routine checking of oil pressures on such feeders.

On comparing the actual oil pressures with the calculated values derived from the information on the profile, a fairly accurate knowledge of the oil temperatures in the section appears to be important. How do the authors compute their oil temperatures for this purpose?

Referring again to mains records, I do not agree that different types of armouring and servings should be relied upon to identify cables. I feel that the choice of the covering for a cable should not necessarily have any relation to the matter of identification. If the records are accurate and complete, they should be good enough for identification purposes without any special cable covers. An exception to this rule is with cables belonging to different authorities laid adjacent to each other in the same footpath or roadway. In such cases I would use a distinctive cover board or tile over the cable.

Mr. W. D. Lovell: As indicated in the paper, the desirability of organized planning and of the recording of plant maintenance has in recent years been recognized by many large undertakings, and several effective schemes have been evolved. This development has, to my mind, been brought about mainly on account of special local conditions and to some extent by additional complications and automatic features in the design of electrical plant and equipment requiring periodical inspection and attention. In considering any scheme of plant maintenance, I think it is well to bear in mind that, while a scheme may have proved quite successful and beneficial on one undertaking, it does not necessarily mean that the same results will be obtained on another undertaking. Careful preparation and the issuing of detailed instructions on plant maintenance are, I think, very desirable, but what is of greater importance in my opinion is some form of follow-up method to ensure that the work is carried out as planned. It has been my experience that unless some such method is adopted there is a tendency for side-tracking, and if this is not checked a good scheme can become a complete failure.

With regard to the question of staffing, I am in general agreement with the authors' views in the first paragraph of Section 1, except that I favour the placing of all constructional, operational and maintenance work under the same staff. In addition to the advantages mentioned by the authors, this tends to better operational co-operation and also prevents the undesirable formation of watertight compartments and eliminates the overlapping of duties and divided responsibility. Admittedly this method of staffing, when applied to large undertakings, sometimes intro-

duces limitations and certain difficulties, but even so there are undertakings which have successfully overcome such drawbacks without having to resort to decentralization.

From my own experience of the "permit-to-work" system both in this country and overseas, I consider that for large undertakings it is one of the best so far devised. For medium and small undertakings it is questionable whether there is the same need for its use, as there are several good "key" systems less elaborate and equally flexible, which have proved in practice to be quite safe and reliable. Moreover, full advantage of the "permit to work" card system can be obtained only when some form of day-and-night centralized control is established, which is often difficult to justify on small undertakings.

Mr. E. E. Dunn: In connection with oil-filled cables, the authors include in their data pressure/volume curves for tanks. Is each curve for a group of tanks operating as a unit on each oil section? Would the authors say how they use these curves, seeing that the cable oil-pressure limits are indicated on the profile, Fig. 14?

Apart from moisture, have the authors found that a progressive decrease in insulation resistance is characteristic of any particular form of deterioration of transformer insulation? Regarding the reference to routine tests on 66-kV switchgear bushings, have the authors fixed upon any degree of power-factor change in excess of which they take bushings out of service? What testing voltage is used?

Mr. W. G. Guns (*communicated*): Where do the authors recommend that maintenance instructions for apparatus should be kept? In the head office, in the district engineer's office, in a desk or cupboard at the station or substation concerned, or in a pocket on, or attached to, the apparatus concerned, with limitation of quantity to one where identical apparatus is installed?

Mr. D. Riach (*communicated*): Small wiring connections not properly refixed after disconnection are a common source of trouble on distribution switchboards. The standard method is to bolt the connections. In my view this type of connection is appropriate only if the duty involves frequent disconnecting. There ought, however, to be no occasion for disconnecting small wiring, either prior to or after commissioning switchgear, and I suggest that soldered connections would be more appropriate. Soldering lugs should take the place of screws for the terminals of the panel instruments and terminal boards, etc. As a result, the procedure for testing, commissioning and maintenance would help to avoid disconnecting small wiring.

The authors advise that the use of master keys for operating locks on high-voltage apparatus should be forbidden. Does this mean that master keys should not be available even to the authority forbidding their use?

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. F. N. Beaumont and **F. A. Geary** (*in reply*): We refer to our reply to the London discussion* to many points raised, particularly on the question of staffing. The "permit-to-work" card system must be based on a rigid code of rules; the operation of switchgear and the proving of apparatus safe to work on are the responsibility of the authorized person, and he alone should have access to keys. On our undertakings isolator keys controlling circuits earthed for work on mains are handed to the mains engineer and a "permit-to-work" card is issued to him.

Replies to points of individual interest are made below.

Messrs. Oswald, Calwell, Rowan, Coates and Dixon.—The hermetically-sealed transformer is suitable for use either under or above ground, the basic principle being the exclusion of moisture and oxygen. When used underground, the surrounding tank is merely air-filled. Transformers of standard design as regards iron and copper losses have been used, i.e. for a 120-kVA 3-phase 3 300/400/230-volt transformer the iron loss is 700 watts, and the copper loss 2 000 watts; but for completely unventilated positions a design is used with an iron loss of 460 watts, and a copper loss of 1 300 watts. There is little difference between the temperature of the oil and that of the ambient air, as the only radiation is that absorbed by the soil surrounding the containing tank; but oil temperatures up to 60° C are obtained underground with load factors of 30% or higher, and during periods of full maximum demand. These transformers are so reliable that the condition of the oil is found to be as good as new after five years' service with no intervening inspection; this fact alone justifies a 20% increase in initial cost. We see no reason why higher voltage equipment, say of 11 000 volts, should not be equally satisfactory.

Mr. Hanna.—The blotting-paper filter press has the disadvantage of introducing fibres into the oil, making it advisable to pass the oil through a centrifuge afterwards. This disadvantage has been overcome in a design using paper discs with edgewise filtration, the oil finally passing into a chamber under vacuum for the extraction of moisture, etc. The efficiency of the cold-filtration type with a bed of kieselguhr and charcoal is increased by periodic cleaning of the tubes and serrated washers. We consider that the filter type is the most effective for solid impurities and semi-colloidal carbon. The detailed examination of transformers advocated is generally only possible on site with small units.

Mr. Henderson.—We endorse the views of Mr. Henderson, especially regarding the use of detectors on metalclad equipment. Earthing gear for metalclad switchgear is often cumbersome and inefficient, and there is scope for its improvement. Apart from metering tanks forming a part of the switchgear, metering *per se* was considered to be outside the scope of the paper.

Mr. Stevenson.—In neither of our undertakings are h.v. cables periodically tested with h.v. direct current. We consider this most undesirable. The 0·4 in² four-core l.v. cable shown in one of the diagrams is not modern and is not included in our suggestions for standardization, which are made for the future and based on experience.

Mr. Easton.—We agree that maintenance problems will be reduced, but only as a result of systematic records taken by the maintenance engineer and passed to the designer, so that the necessary modifications may be made to items found to require excessive attention.

Mr. Bell.—We abandoned primary tripping batteries many years ago; the alkaline or lead-acid battery is more flexible and, in our opinion, more suitable for such duties. The inherent disadvantages of cables drawn into ducts were mentioned in the paper, but probably electrolytic action is avoided with directly-laid cables by using compounded hessian serving. Plain lead-covered cables with this serving should be free from electrolytic action when drawn into ducts. The scope of the paper precluded a Section on fault location; we use an h.v. direct-current bridge for locating faults on h.v. cables and obtain remarkably accurate results.

Mr. Grafton.—On one of the authors' undertakings the automatic feature of CO_2 installations is made inoperative in the section where any maintenance work is proceeding; the manual feature is then relied upon.

Mr. Hurworth.—The variant of the "permit-to-work" card system raises some interesting points. The maintenance fitter or

* *Journal I.E.E.*, 1944, 91, Part II, p. 130.

jointer is employed to carry out work on the plant specified and his participation in operation appears to place on him a measure of responsibility for work he is neither interested in nor competent to judge, and therefore we contend that all operating and proving of apparatus dead be wholly entrusted to a reliable authorized person working with a central control.

Mr. Coates.—We agree that commissioning tests should be based on a detailed and systematic schedule. The experience with earth-fault indicating lamps is interesting.

Dr. McCombe.—Our experience has shown that a private telephone system for inter-station communication combined with the Post Office system meets all requirements, the former being invaluable for system operation and testing. Portable telephones for pilot testing are also useful. We agree with the remarks regarding transport.

Mr. Cooper.—We strongly endorse Mr. Cooper's views regarding the interpretation of the breakdown value of oil; this must be taken in conjunction with tests for clarity, acidity and flash-point. The danger from carbonized oil is that the settling of the carbon on insulators may lead to tracking and failure. The busbar-zone protective scheme detailed has given excellent results and has been free from instability.

Mr. Mann.—Far from objecting to intermixing maintenance and erection staff, we have advocated it in Section 1.

Mr. Sammons.—In the record-card systems detailed we agree that it is essential that all information should be recorded as soon as the work on the equipment is complete; unless this rule is strictly adhered to any record system is misleading and inaccurate.

Mr. Macdonald.—The maximum-demand ammeter used in underground transformer tanks is of the ordinary thermal type. We agree that it is impossible to relate the capacity of h.r.c. fuses to more than one factor; we therefore ignore overload protection for distribution transformers and protect against faults, either on the transformer or network. The loading per cubic foot for switchroom heating is based on site conditions and humidity. A certain large underground switch house has a loading of 0·6 watt/ft^3 with 50% of the tubular heaters controlled by thermostats; whereas a humid site above ground with open front canopied switchgear has a loading of 2·0 watt/ft.^{3} Over-current protection is always a useful back-up feature on balanced schemes; whether it could be dispensed with will depend on system layout and possible future network modifications.

Mr. Heppenstall.—The time intervals in the schedules are chiefly maximum ones except where stated; more frequent inspections may be necessary in special cases. Increasing the time intervals often leads to neglect of plant.

Mr. Lambert.—Regarding explosion diaphragms, we have experience of glass and Bakelized linen; the latter deteriorates in time but appears reasonably sensitive, although most types appear unreliable in their performance and are influenced by the position of the explosion relative to the diaphragm.

Mr. Dixon.—We favour cold filtration of oil whenever possible and cannot agree that time is saved by pre-heating. The disadvantage of Penetrol is that no standard oil purifier will deal with it at ambient temperature. Our experience has been that the centrifuge is the most effective purifier when dealing with this type of oil with a high moisture content. It is not claimed that the acidity value of oil is reduced by the commercial purifier, but the removal of sludge, etc., by regular purification of transformer oil improves the efficiency of the cooling system and hence minimizes the tendency towards acid formation. Warm, dry air passing from the conservator through the silica-gel breather during the loading cycle has a small regenerative effect. We do not agree that H-type cable is as satisfactory as oil-filled cable for 33 kV in service. The cost of maintenance of oil-filled cable is restricted to three-monthly pressure readings; the comparison between the H-type and the oil-filled type is proportional to the safety factor desired.

Mr. McCulloch.—With trickle-charged batteries, we agree that a supplementary full-rate discharge test is beneficial; also a gassing charge after topping up. Our views on the use of h.r.c. fuses are referred to in our reply to Mr. Macdonald.

Mr. Bates.—We have no oil-filled cable routes not provided with automatic leak indicators and, with regard to the routine checking of oil pressures, we suggest a series of short-period readings in the initial stages of installation. In comparing the actual oil pressures with the calculated values derived from the information on the profile, the oil temperatures of sections are taken at the same time as pressure readings, the thermometer being immersed in the gauge connection of the pressure tank. These values are compared with those calculated from cable loading and ground temperatures.

Mr. Dunn.—Power-factor routine testing of 66-kV bushings is carried out at 38 kV. The change in power factor is more important than the absolute figure, but a bushing having a power factor greater than 4% is subjected to special investigation and tests. The curves in Fig. 14 for oil-filled cables refer to each individual section. Curves are used to denote any subsequent collapse of internal diaphragms due to leakage or imperfection in manufacture.

Mr. Guns.—Our practice is for all records relating to distribution to be kept in the district engineer's office.

Mr. Riach.—We consider that the danger of loose terminal connections on instruments and relays is exaggerated; the bolted connection has much to commend it. We adhere to our statement that no master keys should be available to anyone for operating locks on high-voltage apparatus.